Vaccine Development Strategies for SARS-CoV-2

This manuscript ([permalink](https://greenelab.github.io/covid19-review/v/628ef29df15bdfd9a5ba75f477f45292fbd8a6e1/)) was automatically generated from [greenelab/covid19-review@628ef29](https://github.com/greenelab/covid19-review/tree/628ef29df15bdfd9a5ba75f477f45292fbd8a6e1) on April 25, 2022. It is also available as a [PDF](https://greenelab.github.io/covid19-review/v/628ef29df15bdfd9a5ba75f477f45292fbd8a6e1/manuscript.pdf). It represents one section of a larger evolving review on SARS-CoV-2 and COVID-19 available at <https://greenelab.github.io/covid19-review/>

**This in progress manuscript is not intended for the general public.** This is a review paper that is authored by scientists for an audience of scientists to discuss research that is in progress. If you are interested in guidelines on testing, therapies, or other issues related to your health, you should not use this document. Instead, you should collect information from your local health department, the [CDC’s guidance](https://www.cdc.gov/coronavirus/2019-ncov/index.html), or your own government.

# Authors

**COVID-19 Review Consortium:** Vikas Bansal, John P. Barton, Simina M. Boca, Joel D Boerckel, Christian Brueffer, James Brian Byrd, Stephen Capone, Shikta Das, Anna Ada Dattoli, John J. Dziak, Jeffrey M. Field, Soumita Ghosh, Anthony Gitter, Rishi Raj Goel, Casey S. Greene, Marouen Ben Guebila, Daniel S. Himmelstein, Fengling Hu, Nafisa M. Jadavji, Jeremy P. Kamil, Sergey Knyazev, Likhitha Kolla, Alexandra J. Lee, Ronan Lordan, Tiago Lubiana, Temitayo Lukan, Adam L. MacLean, David Mai, Serghei Mangul, David Manheim, Lucy D'Agostino McGowan, Jesse G. Meyer, Ariel I. Mundo, Amruta Naik, YoSon Park, Dimitri Perrin, Yanjun Qi, Diane N. Rafizadeh, Bharath Ramsundar, Halie M. Rando, Sandipan Ray, Michael P. Robson, Vincent Rubinetti, Elizabeth Sell, Lamonica Shinholster, Ashwin N. Skelly, Yuchen Sun, Yusha Sun, Gregory L Szeto, Ryan Velazquez, Jinhui Wang, Nils Wellhausen

Authors with similar contributions are ordered alphabetically.

## 0.1 Abstract

Vaccines have revolutionized the relationship between people and disease. In the 21st century, several emergent viruses have emphasized the particular value of rapid and scalable vaccine development programs. During the current pandemic caused by *Severe acute respiratory syndrome coronavirus 2* (SARS-CoV-2), recent biotechnological advances in vaccine design have facilitated the development and deployment of vaccines at an unprecedented pace. The genome sequence of SARS-CoV-2 was released in January 2020, allowing for global efforts in vaccine development to begin within two weeks of the international community becoming aware of the new viral threat. Both established vaccine platforms and more recently developed technologies have been explored against SARS-CoV-2. Although historically a slow process, vaccine development in the face of COVID-19 accelerated so much that less than a year into the pandemic, some vaccine candidates had reported interim phase III clinical trial data and were being administered in countries around the world.

In this review, we contextualize COVID-19 vaccine development in the broader vaccine landscape. We describe where these candidates currently stand in terms of efficacy, safety, and approval and discuss patterns in worldwide distribution. Vaccines have nearly 500 years of history, but the SARS-CoV-2 pandemic provides an exceptional illustration of how rapidly vaccine development technology has advanced in the last two decades in particular.

## 0.2 Importance

The SARS-CoV-2 pandemic has caused untold damage globally, presenting unusual opportunities and demands in vaccine development. As of April 22, 2022, SARS-CoV-2 has infected over 508,708,154 and taken the lives of 6,215,601 people globally. The development, production, and distribution of vaccines is imperative to saving lives, preventing illness, and reducing the economic and social burdens caused by the COVID-19 pandemic. Effective deployment is critical to reducing the susceptibility of worldwide populations, especially in light of emerging variants. This review provides historical context for the current state of vaccine development and highlights the main strategies utilized for COVID-19 vaccine candidates, their clinical appraisal, and their distribution. These technologies have revolutionized the timescale at which countries can mount a response to an emerging viral threat and provide potential for mitigating future threats before their damage reaches the levels caused by SARS-CoV-2. As the SARS-CoV-2 virus has evolved, they also provide insight into how these technologies have to adapt on incredibly short timescales.

## 0.3 Introduction

The development of vaccines is widely considered one of the most important medical advances in human history. Over the past 150 years, several new approaches to vaccine development have emerged [[1](#ref-YY3x3bBV)]. Today, the requirements for developing and deploying a vaccine are complex and often require coordination between government, industry, academia, and philanthropic entities [[2](#ref-plfPrQP7)]. Flu-like illnesses caused by viruses that follow an annual pattern are a major target of vaccine development programs. However, vaccine development has historically been slow. The past 20 years have seen several previously unknown viruses emerge and rise rapidly to pose a global threat, challenging vaccine developers to explore approaches that would facilitate a rapid response to novel viruses.

Emergent viral threats of the 21st century include severe acute respiratory syndrome (SARS), “swine flu” (H1N1), Middle East respiratory syndrome (MERS), Ebola virus disease (EVD), and now COVID-19, all of which have underscored the importance of a rapid global response to a new infectious virus. Because vaccines fail to provide immediate prophylactic protection or treatment of ongoing infections, their application to most of these epidemics has been limited [[3](#ref-181QWa7HL)]. One of the more successful recent vaccine development programs was for H1N1 influenza. This program benefited from the strong existing infrastructure for influenza vaccines along with the fact that regulatory agencies had determined that vaccines produced using egg- and cell-based platforms could be licensed under the regulations used for a strain change [[4](#ref-HyYY2agc)]. Although a monovalent H1N1 vaccine was not available before the pandemic peaked in the United States and Europe, it became available soon afterward as a stand-alone vaccine that was eventually incorporated into commercially available seasonal influenza vaccines [[4](#ref-HyYY2agc)]. Critiques of the production and distribution of the H1N1 vaccine have stressed the need for alternative development-and-manufacturing platforms that can be readily adapted to new pathogens.

Vaccine technologies that require only minor adjustments for novel viral threats are appealing because this modular approach would mean they could enter trials quickly in response to a new pathogen of concern. Traditional vaccine technologies were built on the principle of using either a weakened version of the virus or a fragment of the virus, while recent years have seen a paradigm shift towards reverse vaccinology. Reverse vaccinology emphasizes a hypothesis-free approach to vaccine development [[5](#ref-jU9YFYvB)]. This strategy was explored during development of a DNA vaccine against the Zika virus [[6](#ref-u0dESADU)]. While once again the disease was controlled before the vaccine became available [[4](#ref-HyYY2agc)], the response demonstrated the potential for modular technologies to facilitate a response to emerging viral threats [[6](#ref-u0dESADU)]. The potential for such vaccines to benefit the field of oncology has encouraged vaccine developers to invest in next-generation approaches, which has spurred the diversification of vaccine development programs [[7](#ref-wPl93ATP),[8](#ref-BsrTDzJ2)]. As a result, during the COVID-19 pandemic, these modular technologies have taken center stage in controlling a viral threat for the first time.

The pandemic caused by SARS-CoV-2 has highlighted a confluence of circumstances that positioned vaccine development as a key player in efforts to control the virus and mitigate its damage. This virus did not follow the same trajectory as other emergent viruses of recent note, such as SARS-CoV-1, MERS-CoV, and Ebola virus, none of which reached the level of pandemic. Spread of the SARS-CoV-2 virus has remained out of control in many parts of the world into 2022, especially with the emergence of novel variants exhibiting increased rates of transmission [[9](#ref-GdZc4Yyd)]. While, for a variety of reasons, SARS-CoV-2 was not controlled as rapidly as the viruses underlying prior 21st century epidemics [[10](#ref-njpLhBui)], vaccine development technology had also progressed based on these and other prior viral threats to the point that a rapid international vaccine development response was possible.

Vaccines bolster the immune response to the virus at the population level, thereby driving a lower rate of infection and likely significantly reducing fatalities even for a highly infectious virus like SARS-CoV-2. The first critical step towards developing a vaccine against SARS-CoV-2 was characterizing the viral target, which happened extremely early in the COVID-19 outbreak with the sequencing and dissemination of the viral genome in early January 2020 [[11](#ref-vlGP3RAU)] (Figure [1](#fig:virus)). This genomic information allowed for an early identification of the sequence of the spike (S) protein (Figure [1](#fig:virus)), which is the antigen and induces an immune response [[12](#ref-Vnbw9o3T),[13](#ref-13wCBLnnu)].

The Coalition for Epidemic Preparedness Innovations (CEPI) is coordinating global health agencies and pharmaceutical companies to develop vaccines against SARS-CoV-2. As early as September 2020, there were over 180 vaccine candidates against SARS-CoV-2 in development [[14](#ref-dqpEe5Lz)]. While little is currently known about immunity to SARS-CoV-2, vaccine developers typically tests for serum neutralizing activity, as this has been established as a biomarker for adaptive immunity in other respiratory illnesses [[15](#ref-wiGjCZC8)]. However, unlike in efforts to develop vaccines for prior viral threats, the duration of the COVID-19 pandemic has made it possible to test vaccine in phase III trials where the effect of the vaccine on a cohort’s likelihood of contracting SARS-CoV-2 is evaluated. With vaccine candidates at all stages of development, including full approval of some vaccines, the vaccine development landscape for COVID-19 includes vaccines produced by a wide array of technologies. Examining the vaccine development programs tackling the COVID-19 pandemic alongside other 21st century efforts to control emerging viral threats demonstrates the significant biotechnological advances in this field and the importance of modular and adaptable approaches to vaccination. Here, we review the various technologies being explored for the development of SARS-CoV-2 vaccines globally.



Figure 1: **Structure of the SARS-CoV-2 virus.** The development of vaccines depends on the immune system recognizing the virus. Here, the structure of SARS-CoV-2 is represented both in the abstract and against a visualization of the virion. The abstracted visualization was made using BioRender [[16](#ref-14FBejgLM)] and the microscopy was conducted by the National Institute of Allergy and Infectious Diseases [[17](#ref-Jzj97hJh)].

## 0.4 Cross-Platform Considerations in Vaccine Development

Certain design decisions are relevant to vaccine development across multiple platforms. One applies to platforms that deliver the antigen, which in the case of SARS-CoV-2 vaccines is the Spike (S) protein. The prefusion conformation of the SARS-CoV-2 S protein, which is the structure before the virus fuses to the host cell membrane, is metastable [[18](#ref-R7Xdh5nH)], and the release of energy during membrane fusion drives this process forward following destabilization [[19](#ref-17DSmRo9H),[20](#ref-3uddYea8)]. Due to the significant conformational changes that occur during membrane fusion [[21](#ref-qcVbT0w4),[22](#ref-hIc3bKWe),[23](#ref-zK0rFpz1)], S protein immunogens that are stabilized in the prefusion conformation are of particular interest, especially because a prefusion stabilized MERS-CoV S antigen was found to elicit an improved antibody response [[24](#ref-oghHqZDt)]. Moreover, the prefusion conformation offers an opportunity to target S2, a region of the S protein that accumulates mutations at a slower rate [[24](#ref-oghHqZDt),[25](#ref-13wWdgODZ),[26](#ref-OVsxrEuX)] (see also [[9](#ref-GdZc4Yyd)]). Vaccine developers can stabilize the prefusion conformer by selecting versions of the S protein containing mutations that lock the position [[27](#ref-lvq9hGmj)]. The immune response to the spike protein when it is stabilized in this conformation is improved over other S structures [[28](#ref-10UC562ga)]. Thus, vaccines that use this prefusion stabilized conformation are expected to not only offer improved immunogenicity, but also be more resilient to the accumulation of mutations in SARS-CoV-2.

Another cross-platform consideration is the use of adjuvants. Adjuvants include a variety of molecules or larger microbial-related products that affect the immune system broadly or an immune response of interest. They can either be comprised of or contain immunostimulants or immunomodulators. Adjuvants are sometimes included within vaccines in order to enhance the immune response. Different adjuvants can regulate different types of immune responses, so the type or combination of adjuvants used in a vaccine will depend on both the type of vaccine and concern related to efficacy and safety. A variety of possible mechanisms for adjuvants have been investigated [[29](#ref-13bVbfc5h),[30](#ref-122h6fIxE),[31](#ref-uO0uqhxc)].

## 0.5 COVID-19 Vaccine Development Platforms



Figure 2: **Vaccine Development Strategies.** Several different strategies can and are being employed for the development of vaccines today. Each approach capitalizes on different features of the SARS-CoV-2 virus and delivery through a different platform. All of these approaches are being explored in the current pandemic.

The first administration of a dose of a COVID-19 vaccine to a human trial participant occurred on March 16, 2020 [[32](#ref-fQvzeptv),[33](#ref-1GA95MF2m)], marking an extremely rapid response to the emergence of SARS-CoV-2. Within a few weeks, at least 78 vaccine development programs were active [[33](#ref-1GA95MF2m)]. These programs employ a variety of technologies (Figure [2](#fig:vaccines)), ranging from established approaches to novel technologies that had never previously gone to market. As of April 21, 2022, 38 SARS-CoV-2 vaccines have been approved world wide and 26 are being administered throughout the world, with 12 billion doses administered across 223 countries. Many vaccines are available in only a subset of countries, and the types of vaccines available varies widely throughout the world. The status of individual vaccines continues to change and varies regionally.

### 0.5.1 Whole-Virus Vaccines

Whole-virus vaccines have the longest history among vaccine development approaches. Variolation, which is widely considered the first vaccination strategy in human history, is one example [[34](#ref-Q10m9bJ),[35](#ref-1Clt2Bek3)]. Famously employed against smallpox when healthy individuals were exposed to pus from an individual infected with what was believed to be either cowpox or horsepox [[34](#ref-Q10m9bJ),[35](#ref-1Clt2Bek3),[36](#ref-ZUHALvLg),[37](#ref-1DFnwhtrq)], variolation allowed healthy individuals to be infected with a mild case of a disease. While whole-virus vaccines can confer adaptive immunity, they also face safety concerns [[36](#ref-ZUHALvLg),[38](#ref-kC2tx3JC),[39](#ref-K0Ltu31S)]. As of 2005, most vaccines still used whole-virus platforms [[40](#ref-U9ZIZWkB)], and these technologies remain valuable tools in vaccine development today [[1](#ref-YY3x3bBV)]. Whole virus vaccine candidates have been developed for COVID-19 using both live attenuated viruses and inactivated whole viruses.

Table 1: Approved whole-virus vaccines [[41](#ref-jswAyWIs)]

| Vaccine | Company |
| --- | --- |
| Covaxin | Bharat Biotech |
| KoviVac | Chumakov Center |
| Turkovac | Health Institutes of Turkey |
| FAKHRAVAC (MIVAC) | Organization of Defensive Innovation and Research |
| QazVac | Research Institute for Biological Safety Problems (RIBSP) |
| KCONVAC | Shenzhen Kangtai Biological Products Co |
| COVIran Barekat | Shifa Pharmed Industrial Co |
| Covilo | Sinopharm (Beijing) |
| Inactivated (Vero Cells) | Sinopharm (Wuhan) |
| CoronaVac | Sinovac |
| VLA2001 | Valneva |

#### 0.5.1.1 Live-Attenuated Virus Vaccines

**Mechanism:** LAV, also known as replication-competent vaccines, use a weakened, living version of a disease-causing virus or a version of a virus that is modified to induce an immune response [[14](#ref-dqpEe5Lz)]. Whether variolation is the first example of a live-attenuated virus (LAV) being used to induce immunity is debated [[1](#ref-YY3x3bBV),[38](#ref-kC2tx3JC)], but subsequent efforts to incorporate attenuated viruses relied on either the identification of related viruses that were less virulent in humans (e.g., cowpox/horsepox or rotavirus vaccines) or culture of a virus in vitro [[1](#ref-YY3x3bBV),[36](#ref-ZUHALvLg)]. Today, a virus can be attenuated by passaging it in a foreign host until, due to selection pressure, the virus loses its efficacy in the original host. Alternatively, selective gene deletion or codon de-optimization can be utilized to attenuate the virus [[14](#ref-dqpEe5Lz)]. Foreign antigens can also be integrated into an attenuated viral vector [[42](#ref-4RuaSyLg)]. LAVs are also favored because they tend to be restricted to viral replication in the tissues around the location of inoculation [[43](#ref-iX8wXLPW)], and some can be administered intranasally [[14](#ref-dqpEe5Lz)].

**Prior Applications:** The first deliberate (albeit pathogen-naïve) attempt to develop an attenuated viral vaccine dates back to Louis Pasteur in 1885. The next intentional LAVs were developed against the yellow fever virus in 1935 and influenza in 1936 [[43](#ref-iX8wXLPW)]. Today, LAVs are used globally to prevent diseases caused by viruses such as measles, rubella, polio, influenza, varicella zoster, and the yellow fever virus [[44](#ref-wZ2tXSUH)]. There were attempts to develop LAVs against both SARS-CoV-1 and MERS-CoV [[45](#ref-7RHpaAHu)], but no vaccines were approved.

**Application to COVID-19:** LAVs have not been widely utilized against SARS-CoV-2 and COVID-19. All the same, there are at least five COVID-19 LAV candidates in the early (preclinical/phase I) stages of investigation. These candidates utilize different approaches. In one case, the vaccine delivers a noncleavable SARS-CoV-2 antigen prefusion conformation using a live-attenuated yellow fever virus [[42](#ref-4RuaSyLg)]. Several other candidates use codon-deoptimized SARS-CoV-2 [[46](#ref-nwyfEEPl),[47](#ref-iCUWeMfX),[48](#ref-xMxJTYge)], leveraging the fact that different organisms display different biases in which synonymous codons are preferred to select codons that will be less optimal in the target organism without altering the amino acids encoded [[49](#ref-P329FxPV)]. Another is a chimeric vaccine that integrates genomic content from multiple viruses to create a more stable LAV [[50](#ref-14GSJSuHC)]. A final LAV being evaluated against COVID-19 was not specifically developed against SARS-CoV-2; instead, Bacillus Calmette-Guerin (BCG) vaccines were being investigated for the prophylaxis of COVID-19 [[51](#ref-1CJtdlM6d)] because they are known to exert protective non-specific effects against other respiratory tract infections in in vitro and in vivo studies [[52](#ref-16FOT89K5)]. However, a multicenter trial that randomly assigned participants 60 years and older to vaccination with BCG (n = 1008) or placebo (n = 1006) after 12 months of follow-up found that BCG vaccination had no effect on the incidence of SARS-CoV-2 or other respiratory infections [[53](#ref-eHrzWQ6D)]. Despite these negative findings, BCG vaccination did induce a stronger antibody and cytokine response following COVID-19 infection.

**Safety and Efficacy:** Data is not yet available for human studies. In general, though safety associated with the production of LAVs was a major concern in the past, today manufacturers use safe and reliable methods to produce large quantities of vaccines once they have undergone rigorous preclinical studies and clinical trials to evaluate their safety and efficacy. However, one reason underlying the relatively slow emergence of LAV candidates against COVID-19 may be the risk presented to individuals who are immunocompromised [[54](#ref-bgKUtUIL)], which is an even greater concern when dealing with a novel virus and disease. Additionally, it is generally recognized that LAVs induce an immune response similar to natural infection, and they are favored because they induce long-lasting and robust immunity that can protect from disease. This strong protective effect is induced in part by the immune response to the range of viral antigens available from LAV, which tend to be more immunogenic than those from non-replicating vaccines [[38](#ref-kC2tx3JC),[45](#ref-7RHpaAHu),[55](#ref-zLL2yOJK)]. Additional data are needed to ascertain how this technology performs in the case of SARS-CoV-2.

#### 0.5.1.2 Inactivated Whole-Virus Vaccines

**Mechanism:** Inactivated whole-virus (IWV) vaccines are another well-established technology. These types of vaccines use full virus particles generally produced via cell culture that have been rendered non-infectious by chemical (i.e., formaldehyde or β-propiolactone [[56](#ref-PwjPrwXa)]) or physical (i.e., heat or ultraviolet radiation) means. In general, these vaccines mimic the key properties of the virus that stimulate a robust immune response, but the risk of adverse reactions is reduced because the virus is inactivated and thus unable to replicate. Though these viral particles are inactivated, they retain the capacity to prime the immune system. The size of the virus particle makes it ideal for uptake by an antigen-presenting cell (APC), which leads to the stimulation of helper T-cells [[57](#ref-7Knbo28h)]. Additionally, the array of epitopes on the surface of the virus increases antibody binding efficiency [[57](#ref-7Knbo28h)]. The native conformation of the surface proteins, which is also important for eliciting an immune response, is preserved using these techniques [[58](#ref-10peSXMZx)]. Membrane proteins, which support B-cell responses to surface proteins, are also induced by this method [[59](#ref-iAa7uWOm)].

**Prior Applications:** IWV vaccines have been a valuable tool in efforts to control many viruses. Some targets of IWV vaccines have included influenza viruses, poliovirus, and hepatitis A virus. Inactivated vaccines are generally considered the fastest to generate once the pathogenic virus has been isolated and can be passaged in cell culture [[45](#ref-7RHpaAHu)], although this has not been the case for the COVID-19 pandemic. Past applications to HCoV have focused predominantly on SARS-CoV-1.

Preclinical studies have demonstrated that IWV SARS-CoV-1 vaccine candidates elicited immune responses *in vivo*. These vaccines generated neutralizing antibody titers at concentrations similar to those evoked by recombinant protein vaccines [[58](#ref-10peSXMZx),[60](#ref-1DymXCWa0)]. Studies in ferrets and non-human primates demonstrated that IWV vaccines can offer protection against infection due to neutralizing antibody and SARS-CoV-1-specific T cell responses [[61](#ref-4Hh1wpwV)].

However, several attempts to develop IWV vaccines against both SARS-CoV-1 and MERS-CoV were hindered by incidences of vaccine-associated disease enhancement (VADE) in preclinical studies [[62](#ref-4AwyoMvQ)]. In one example of a study in macaques, an inactivated SARS-CoV-1 vaccine induced even more severe lung damage than the virus due to an enhanced immune reaction [[63](#ref-ZXAfLbxM)]. Independent studies in mice also demonstrated evidence of lung immunopathology due to VADE in response to MERS-CoV IWV vaccination [[64](#ref-ihrfEtMq),[65](#ref-8qw9OBKX)]. The exact mechanisms responsible for VADE remain elusive due to the specificity of the virus-host interactions involved, but VADE is the subject of investigation in preclinical SARS-CoV-2 vaccine studies to ensure the safety of any potential vaccines that may reach phase I trials and beyond [[62](#ref-4AwyoMvQ)].

**Application to COVID-19:** Several whole-virus vaccines have been developed against COVID-19 and are available in countries around the world. As of April 21, 2022, 11 vaccines developed with IWV technology are being distributed in 113 countries (Figure [3](#fig:iwv-distrib)). One, CoronaVac, was developed by Beijing-based biopharmaceutical company Sinovac. They inactivated a SARS-CoV-2 strain collected in China with β-propiolactone and propagated it using Vero cells [[45](#ref-7RHpaAHu)]. The vaccine is coupled with an aluminum adjuvant [[45](#ref-7RHpaAHu)]. In phase I and II clinical trials, CoronaVac elicited a strong immunogenic response in animal models and the development of neutralizing antibodies in human participants [[66](#ref-Ozya5HP5),[67](#ref-14fILrRWg),[68](#ref-N1txjPtt)]. Administration followed a prime-boost regimen using a 0.5 ml dose containing 3 μg of inactivated SARS-CoV-2 virus per dose [[69](#ref-1A5wiKQAW)]. Results from a two-dose phase III trial following a 14-day prime boost became available in late 2020 [[70](#ref-1FF7JOwSH)], and an interim analysis identified specific IgG neutralizing antibodies against S1-RBD and a robust IFN-γ secreting T cell response was induced via immunization with CoronaVac [[71](#ref-UERG6dAd)]. CoronaVac was approved for use in China and has been granted emergency use in XX countries, including Brazil, Cambodia, Chile, Colombia, Laos, Malaysia, Mexico, Turkey, Ukraine, and Uruguay [82]. In August 2021, Sinovac reported that they had produced over a billion doses of CoronaVac [[72](#ref-wByD9WaX)].

Similarly, two inactivated vaccine candidates were developed following a similar approach by the stated-owned China National Pharmaceutical Group Co., Ltd., more commonly known as Sinopharm CNBG. Their BBIBP-CorV vaccine was developed in Beijing using the HB02 strain of SARS-CoV-2. At their Wuhan Institute, they developed a second vaccine using the WIV04 strain of SARS-CoV-2 [[73](#ref-miMRIMwa)]. The viruses were purified, propagated using Vero cells, isolated, and inactivated using β-propiolactone [[73](#ref-miMRIMwa),[74](#ref-VlnLw2HV)]. These vaccines are adjuvanted with aluminum hydroxide [[73](#ref-miMRIMwa),[74](#ref-VlnLw2HV)]. Preclinical studies indicated that the BBIBP-CorV vaccine induced sufficient neutralizing antibody titers in mice, and a prime-boost immunization scheme of 2 μg/dose was sufficient to protect rhesus macaques from disease [[74](#ref-VlnLw2HV)]. For the other vaccine, neutralizing antibodies were detected in all groups 14 days after the final dose in the phase I part of the trial [[75](#ref-T3MYavsH)], with similar findings reported in interim phase II data [[75](#ref-T3MYavsH)].

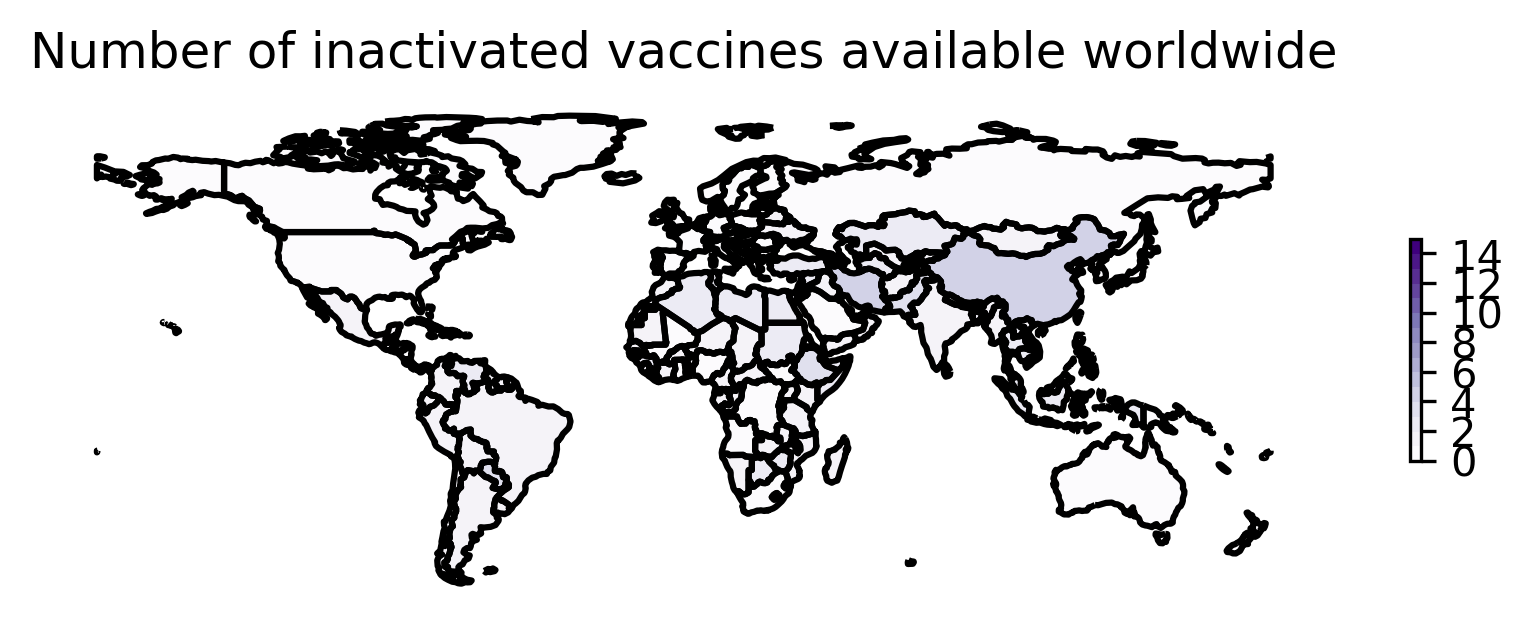


Figure 3: **Worldwide availability of vaccines developed using inactivated whole viruses.** This figure reflects the number of vaccines based on whole inactivated virus technology that were available in each country as of April 21, 2022. These data are retrieved from Our World in Data <!-To Do: Cite–> and plotted using geopandas. See https://greenelab.github.io/covid19-review/ for the most recent version of this figure, which is updated daily.

Other programs have been led through industry partnerships with governmental organizations. Another IWV vaccine comes from India, where Bharat Biotech International Ltd., which is the biggest producer of vaccines globally, Bharat Biotech International Ltd., collaborated with the Indian Council of Medical Research (ICMR) - National Institute of Virology (NIV) to develop COVAXIN®, also referred to as BBV152. Preclinical studies of COVAXIN® in hamsters [[76](#ref-bcGxW9fA)] and macaques [[77](#ref-GgdjKrYi)] indicated that the vaccine induced protective responses deemed sufficient to move forward to human trials. Phase I and phase I/II studies indicated that COVAXIN® adjuvanted with alum and a Toll-like receptor 7/8 (TLR7/8) agonist was safe and immunogenic and that it induced Th1-skewed memory T-cell responses [[78](#ref-CGuGeB7m),[79](#ref-GxQSMH5l)]. As of September 2021, COVAXIN® has been approved for emergency use in Guyana, India, Iran, Zimbabwe, and Nepal, Mauritius, Mexico, Nepal, Paraguay, and the Philippines [[80](#ref-19tYVbg8H)].

**Trial Safety and Efficacy:** In general, IWV vaccine candidates have been well-tolerated in clinical trials. Safety analysis of the CoronaVac vaccine during the phase II trial revealed that most adverse reactions were either mild (grade 1) or moderate (grade 2) in severity. In adults aged 18 to 59 years receiving a variety of dosage schedules, site injection pain was consistently the most common symptom reported [[68](#ref-N1txjPtt)]. In older adults, the most common local and systemic reactions were pain at the injection site (9%) and fever (3%), respectively [[66](#ref-Ozya5HP5)]. In phase III trials, minimal side effects were reported [[70](#ref-1FF7JOwSH)]. For COVAXIN, only mild to moderate side-effects reported upon immunization [[78](#ref-CGuGeB7m),[79](#ref-GxQSMH5l)], and in phase II trials, the BBIBP-CorV vaccine appeared well-tolerated, with 23% of participants in the vaccine condition (482 total participants, 3:1, vaccine:placebo) reporting at least one adverse reaction characterized as mild to moderate [[81](#ref-fPGgVKYL)]. However, both CoronaVac and SinoPharm’s WIV04 vaccine trials were affected by concerns about adverse events. In CoronaVac’s trial of adults 18-59, 2% (n=7) of participants reported severe adverse events [[66](#ref-Ozya5HP5)], causing the trial to be halted for investigation [[82](#ref-aq22z8M7)]. They were determined to be unrelated to the vaccine [[66](#ref-Ozya5HP5)]; [[82](#ref-aq22z8M7)]], which is now widely distributed. Similarly, a trial of the SinoPharm WIV04 vaccine in Peru was briefly paused due to safety concerns in relation to neurological symptoms [[83](#ref-d09adg1G)], but this was later deemed unrelated to the vaccine, and the trial continued [[84](#ref-nxEJTLGU)].

In terms of efficacy, estimates of IWV vaccine efficacy during phase III trials varied widely, and in some cases, even estimates for a single vaccine candidate differed across analyses. In phase III trials, Sinopharm CNBG’s BBIBP-CorV vaccine made from the WIV04 strain achieved an efficacy of 72.8% and was well tolerated [[85](#ref-yN5KOfvE)]. In July 2021, COVAXIN’s overall vaccine efficacy was estimated at 77.8% for the prevention of COVID-19 based on a final enrollment of 25,798 people (~1:1 vaccine:placebo) [[86](#ref-n7BupOQ6)]. Sinopharm affiliates in the UAE in early December 2020 claimed the vaccine had 86% efficacy, which was later at odds with a Sinopharm Beijing affiliate that stated that the BBIBP-CorV vaccine had a 79.34% efficacy later that same month [[87](#ref-w7gO6yGn)]. CoronaVac demonstrated an efficacy of a little over 50% in Brazil, which was contested by Turkish officials claiming an efficacy of 91.25%, but ultimately after multiple announcements, the efficacy debate was settled at over 50% [[88](#ref-18mREgqUz),[89](#ref-V7MXd4X4)]. Subsequently, an interim analysis of the phase III randomized placebo-controlled trials conducted in Turkey enrolling 10,214 participants (~2:1 vaccine:placebo) indicated efficacy of 83.5%, with minimal side effects reported [[70](#ref-1FF7JOwSH)], and a prospective national cohort study in Chile reported an adjusted estimated effectiveness of 66% for the prevention of COVID-19 with an estimated 90% and 87% prevention of hospitalization and death, respectively [[90](#ref-q2wQJULu)]. Therefore, it is difficult to ascribe a particular efficacy to these vaccines given the variation in reports.

**Real-World Safety and Efficacy:** One of the major limitations of IWV vaccines is their susceptibility to losing efficacy due to mutations in the epitopes of the circulating virus [[39](#ref-K0Ltu31S)]. This loss of specificity over time is likely to be influenced by the evolution of the virus, and specifically by the rate of evolution in the region of the genome that codes for the antigen. The beta variant appears to be more resistant to neutralizing antibodies in sera from individuals immunized with Sinovac than the alpha variant or wildtype virus, indicating that emerging variants may be of concern [[91](#ref-s2O5iyCV)]. In agreement with previous studies demonstrating sera from individuals vaccinated with COVAXIN® efficiently neutralized the alpha variant (B.1.1.7) and the delta variant (B.1.617.2) [[92](#ref-lr7INjf6),[93](#ref-UYE3NvU4),[94](#ref-IvOEe7bV)], the phase III trial reported a 65.2% efficacy against the delta variant (B.1.617.2) [[86](#ref-n7BupOQ6)]. However, studies suggested the beta variant was more resistant (compared to the wildtype and alpha variants) to neutralizing antibodies in sera from individuals immunized with Sinovac [[91](#ref-s2O5iyCV)].  
Indeed, another preprint determined that sera from individuals immunized with COVAXIN® had effective neutralizing antibodies against the delta variant and the so-called delta plus variant (AY.1) [[92](#ref-lr7INjf6)]. Notably, a preprint reported that antisera from 12 people immunized with BBIBP-CorV exhibited neutralizing antibody capacity against the beta variant (B.1.351), wild type SARS-CoV-2 (NB02), and one of the original variants of SARS-CoV-2 (D614G) [[95](#ref-w9KwrmQT)]. Another preprint including sera from 282 participants used a surrogate neutralizing assay, a test that generally correlates with neutralizing antibodies, to determine that BBIBP-CorV appears to induce neutralizing antibodies against the binding of the RBD of wild type SARS-CoV-2 and the alpha, beta, and delta variants to ACE2 [[96](#ref-GZ5Sf8Yd)]. Indeed, a study in *The New England Journal of Medicine* showed that the alpha variant exhibited very little resistance to neutralization by sera of those immunized with BBIBP-CorV, but the beta variant was more resistant to neutralization by almost a factor of 3 [[91](#ref-s2O5iyCV)]. The authors noted that no evidence of VADE was detected using this vaccine in phase II data [[75](#ref-T3MYavsH)].

However, concern was raised about the efficacy of CoronaVac following reports that over 350 doctors became ill with COVID-19 in Indonesia despite being immunized with CoronaVac [[97](#ref-fs7G9HyV)]. In addition to concerns raised by the evolution of SARS-CoV-2, it is important to consider the duration of immunity over time. Studies are underway to determine whether a booster immunization is required for several IWV vaccines, including CoronaVac [[98](#ref-1GcPxd9Bn)] and COVAXIN [[99](#ref-s1TGwKbT)]. A phase I/II clinical trial of CoronaVac in an elderly cohort (adults 60 years and older) in China determined that by 6 to 8 months following the second dose, neutralizing antibody titers were detected below the seropositive cutoff [[100](#ref-AcxNwvVQ)]. One preprint has reported that 6 months after the second vaccination, a booster dose of CoronaVac markedly increased geometric mean titers of SARS-CoV-2 neutralizing antibodies [[101](#ref-1BPnaMPs4)]. However, the reduction of neutralizing antibodies was ameliorated by a booster dose administered 8 months after the second CoronaVac dose.

A preprint study of healthcare workers in China has since indicated that a booster shot of BBIBP-CorV elevates B cell and T cell responses and increases neutralizing antibody titers [[102](#ref-QHtyW0Jz)]. In May 2021, the UAE announced it would consider booster shots for all citizens who had been immunized with BBIBP-CorV, which was shortly followed by a similar announcement in Bahrain, and by August 29th, 2021, the UAE mandated booster shots for all residents who had received BBIBP-CorV [[72](#ref-wByD9WaX)]. Additionally, heterogeneous vaccine boosters are also being considered in many cases. Chinese [[103](#ref-9oJ3sbrk)] and Chilean [[104](#ref-rCqhSryT)] researchers have opted to investigate options to administer different vaccines (e.g., an mRNA vaccine dose) as a booster dose to individuals who have already received two doses of CoronaVac. Another study has already determined that using the CanSino vaccine (Convidecia) instead of CoronaVac in a prime-boost vaccination regimen can induce a more robust immune response [[105](#ref-1HVWY0Qmv)]. Today, booster immunization is suggested for several whole-virus vaccines.

### 0.5.2 Subunit Vaccines

Table 2: Approved subunit vaccines [[41](#ref-jswAyWIs)]

| Vaccine | Company | Platform |
| --- | --- | --- |
| Zifivax | Anhui Zhifei Longcom | protein subunit |
| Noora vaccine | Bagheiat-allah University of Medical Sciences | protein subunit |
| Corbevax | Biological E Limited | protein subunit |
| Abdala | Center for Genetic Engineering and Biotechnology (CIGB) | protein subunit |
| Soberana 02 | Instituto Finlay de Vacunas Cuba | protein subunit |
| Soberana Plus | Instituto Finlay de Vacunas Cuba | protein subunit |
| Covifenz | Medicago | VLP |
| MVC-COV1901 | Medigen | protein subunit |
| Recombinant SARS-CoV-2 Vaccine (CHO Cell) | National Vaccine and Serum Institute | protein subunit |
| Nuvaxovid | Novavax | protein subunit |
| Razi Cov Pars | Razi Vaccine and Serum Research Institute | protein subunit |
| COVOVAX (Novavax formulation) | Serum Institute of India | protein subunit |
| TAK-019 (Novavax formulation) | Takeda | protein subunit |
| SpikoGen | Vaxine/CinnaGen Co. | protein subunit |
| Aurora-CoV | Vector State Research Center of Virology and Biotechnology | protein subunit |
| EpiVacCorona | Vector State Research Center of Virology and Biotechnology | protein subunit |

Efforts to overcome the limitations of live-virus vaccines led to the development of approaches first to inactivate viruses (circa 1900), leading to IWV vaccines, and then to purify proteins from viruses cultured in eggs (circa 1920) [[1](#ref-YY3x3bBV),[106](#ref-dggZoRQD)]. The purification of proteins led to the emergence of subunit vaccines. Today, such approaches may use antigens isolated from the surface of the viral particle that are key targets of the immune system (protein subunit vaccines), but advances in biological engineering have also facilitated the development of approaches like viral-like particle (VLP) vaccines using nanotechnology [[107](#ref-99C1xJ2E)].

**Mechanism:** Unlike whole-virus vaccines, which introduce the whole virus, subunit vaccines stimulate the immune system by introducing one or more proteins or peptides of the virus that have been isolated. The main advantage of this platform is that subunit vaccines are considered very safe, as the antigen alone cannot cause an infection [[108](#ref-1FfwyYaj7)]. Both protein subunit and VLP vaccines thus mimic the principle of whole virus vaccines but lack the genetic material required for replication, removing the risk of infection [[109](#ref-1Bxg7Wj6w)]. Protein subunit vaccines can stimulate antibodies and CD4+ T-cell responses [[110](#ref-12eGVhH5I),[111](#ref-lH2HMMZi)]. This platform is also favored for its consistency in production and defined components designed for a highly targeted immune response to a specific pathogen using synthetic immunogenic particles that can be designed to avoid allergen and reactogenic sequences [[112](#ref-124bnGvPp)]. The immune response generated by protein subunit vaccines is weaker, and adjuvants are usually required to boost the response [[113](#ref-mv42t1HV)] (see Appendix). These adjuvants are immunogenic substances, which include, for example, alum (aluminum hydroxide), squalene- or saponin-based adjuvants, and Freund’s incomplete/complete adjuvants [[112](#ref-124bnGvPp),[114](#ref-rioTBsLc)].

**Prior Applications:** Prior protein subunit vaccine development efforts for both SARS-CoV-1 and MERS-CoV have mostly focused on the immunogenic RBD of the S protein [[115](#ref-cLAQnckq),[116](#ref-1EirBATaN),[117](#ref-1AOG59epD)]. There have been several approaches investigated in the search for a potential SARS-CoV-1 vaccine, including vaccines targeting the full-length or trimeric S protein [[118](#ref-Ow2ICHez),[119](#ref-tzZeWNPV)], those focused on the RBD protein only [[115](#ref-cLAQnckq),[116](#ref-1EirBATaN),[117](#ref-1AOG59epD),[120](#ref-DsfTQFmb)] or non-RBD S protein fragments [[119](#ref-tzZeWNPV),[121](#ref-IYjNaaqv)], as well as the N and M proteins [[122](#ref-HvO79P9u),[123](#ref-VUcwpJKL),[124](#ref-7hbgOaiE)]; these efforts have been thoroughly reviewed elsewhere [[125](#ref-9Zv0eLa9)]. There have been examples of success in preclinical research including candidate RBD219N-1, a 218-amino-acid residue of the SARS-CoV-1 RBD that, when adjuvanted to aluminum hydroxide, was capable of eliciting a high RBD-specific and neutralizing antibody response in both pseudovirus and live virus infections of immunized mice [[126](#ref-8723Jsa)]. Several subunit-based approaches have also been used to investigate potential vaccines against MERS. Other strategies investigating the potential use of the full length S DNA have also been investigated in mice and rhesus macaques, which elicited immune responses [[127](#ref-GurQD2dO)], but these responses were not as effective as the combination of S DNA and the S1 subunit protein together [[127](#ref-GurQD2dO),[128](#ref-T7W7hnB9)]. Similarly to the SARS-CoV-1 vaccine candidates, the MERS-CoV protein subunit vaccine candidates generally target the RBD [[116](#ref-1EirBATaN),[125](#ref-9Zv0eLa9),[129](#ref-Mki0DaYb),[130](#ref-aApaHV1w),[131](#ref-deUFGhNI),[132](#ref-sfM5QV3m)], with some targeting the full length S protein [[24](#ref-oghHqZDt)], non-RBD protein fragments such as the SP3 peptide [[133](#ref-11Zz9H0Dl)], and the recombinant N-terminal domain (rNTD) [[134](#ref-ZXsnsfvb)]. No protein subunit vaccine for MERS-CoV has progressed beyond preclinical research to date. VLPs have been investigated for development of vaccines against MERS and SARS [[135](#ref-oqty7gXw),[136](#ref-eHe78HXD)] including testing in animal models [[137](#ref-cnYnzav2),[138](#ref-G87TcArN)], but once again, only preclinical data against HCoV has been collected [[139](#ref-jLJEygoA)]. However, protein subunit vaccines do play a role in public health and have contributed to vaccination against hepatitis B [[140](#ref-155fGivMy)] and pertussis [[141](#ref-CQog2bB7),[142](#ref-1CYqHUt3n)] since the 1980s and will likely continue to contribute to public health for the foreseeable future due to ongoing research in vaccines against influenza, SARS-CoV-2, Epstein-Barr virus, dengue virus, and human papillomavirus among others [[143](#ref-1FQlt5Lqz),[144](#ref-8dSIiLCt),[145](#ref-aAYBP21H)].

**Application to COVID-19:** The development of protein subunit vaccines against SARS-CoV-2 is a remarkable achievement given the short period of time since the emergence of SARS-CoV-2 in 2019, particularly considering these types of vaccines have not played a major role in previous pandemics. More than 20 protein subunit vaccines from companies such as Sanofi/GlaxoSmithKline, Nanogen, and the Serum Institute of India have entered clinical trials for COVID-19 since the beginning of the pandemic [[144](#ref-8dSIiLCt)] and 15 are being administered worldwide [[146](#ref-cWMPXfju)]. VLP vaccines have not progressed as rapidly, with only 1 VLP vaccines approved [[144](#ref-8dSIiLCt)] as of April 21, 2022. Most of these vaccines are designed using either the full-length S protein or the RBD of the S protein specifically as an antigen, although some use several different SARS-CoV-2 proteins [[108](#ref-1FfwyYaj7)]. As of March 30, 2022, 14 protein subunit vaccines are being distributed in 21 countries (Figure 4). As for VLP, 1 vaccine has been approved with distribution in 0 so far.

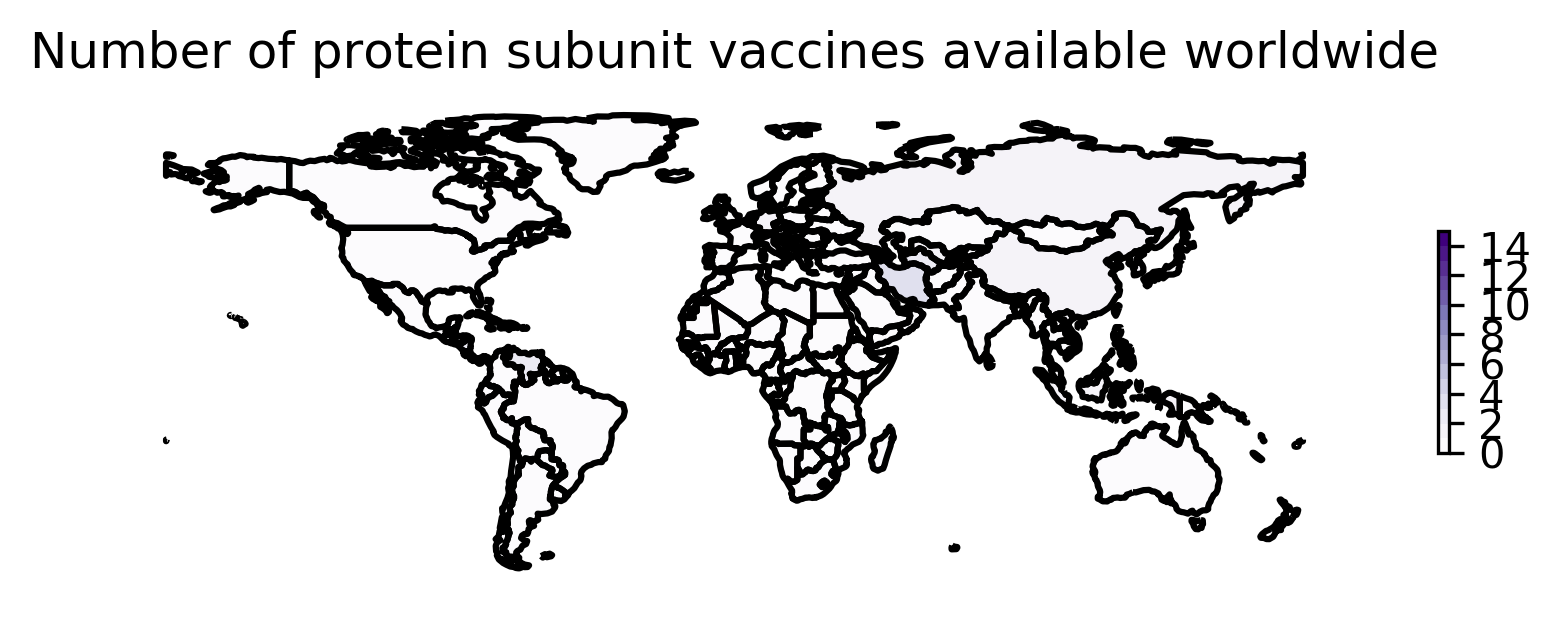


Figure 4: **Worldwide availability of vaccines developed using protein subunit.** This figure reflects the number of vaccines based on protein subunit technology that were available in each country as of April 21, 2022. These data are retrieved from Our World in Data <!-To Do: Cite–> and plotted using geopandas. See https://greenelab.github.io/covid19-review/ for the most recent version of this figure, which is updated daily.

One of the most prominent protein subunit vaccines against SARS-CoV-2 thus far is NVX-CoV2373 or Nuvaxovid, which is produced by U.S. company Novavax and partners. NVX-CoV2373 is a protein nanoparticle vaccine constructed from a mutated prefusion SARS-CoV-2 spike protein in combination with a specialized saponin-based adjuvant to elicit an immune response against SARS-CoV-2. The spike protein is recombinantly expressed in Sf9 insect cells [[147](#ref-Qk33ZrIC)], which have previously been used for several other FDA-approved protein therapeutics [[148](#ref-RQR2sOmx)], and contains mutations in the furin cleavage site (682-RRAR-685 to 682-QQAQ-685) along with two proline substitutions (K986P and V987P) that improve thermostability [[147](#ref-Qk33ZrIC)]. In preclinical mouse models, Novavax-CoV2373 elicited high anti-spike IgG titers 21 to 28 days post-vaccination that could neutralize the SARS-CoV-2 virus and protect the animals against viral challenge, with particularly strong effects when administered with the proprietary adjuvant Matrix-MTM [[147](#ref-Qk33ZrIC)]. In a phase I/II trial, a two-dose regimen of NVX-CoV2373 was found to induce anti-spike IgG levels and neutralizing antibody-titers exceeding those observed in convalescent plasma donated by symptomatic patients [[149](#ref-dMLXxGAI)]. In line with the preclinical studies, the use of Matrix-M adjuvant further increased anti-spike immunoglobulin levels and induced a Th1 response. In a phase III randomized, observer-blinded, placebo-controlled clinical trial in 14,039 participants, two 5-μg doses of NVX-CoV2373 or placebo were administered 21 days apart in a 1:1 ratio from late September to late November 2020 [[150](#ref-1D0f8OrG8)]. Novavax has since been approved in several places, including the United Kingdom [[151](#ref-q3wIcP4d)] and the E.U. [[152](#ref-P3YhxRob)] and applied for an EUA from the FDA in early 2022 [[153](#ref-6mHA0NU9)]. Although Novavax promised to provide up to 1.1 billion doses to COVAX; however, there have been reports of struggle to maintain production capacity and quality, hindering its production targets [[154](#ref-Fw20AJGb)].

**Trial Safety and Efficacy:** In the phase III trial, the efficacy of Novavax was reported to be 89.7%, with a total of 10 patients developing COVID-19 in the vaccine group versus 96 in the placebo group [[150](#ref-1D0f8OrG8)]. No hospitalizations or deaths were reported in the vaccine group. An additional phase III randomized, observer-blinded, placebo-controlled trial was conducted in the U.S. and Mexico, enrolling 29,949 participants and administering at least 1 vaccine in a 2:1 ratio from late December 2020 to late February 2021 with the same primary endpoints as the U.K. trial [[155](#ref-oc5SBo0q)]. A vaccine efficacy of 90.4% was reported based on 77 cases total, 63 of which occurred in the placebo group. All moderate to severe cases of COVID-19 occurred in the placebo group. Additionally, in both trials, the vaccine was found to be well-tolerated [[150](#ref-1D0f8OrG8),[155](#ref-oc5SBo0q)]. The conclusions of both trials indicate that the NVX-CoV2373 vaccine is safe and effective against COVID-19, and those who received this vaccine through the trials are considered fully vaccinated [[156](#ref-1COb5Edqu)].

**Real-World Safety and Efficacy:** To date, data about the effect of viral evolution on the efficacy of subunit vaccines has been limited. *Post hoc* analysis in the phase III trial determined that the NovaVax vaccine had an efficacy of 86.3% against the Alpha variant (identified based on the presence/absence of the 69–70del polymorphism) and 96.4% against other variants [[150](#ref-1D0f8OrG8)]. In the second phase III trial [[155](#ref-oc5SBo0q)], whole-genome sequencing was obtained from 61 of the 77 cases, and 79% of infections were identified as a VOC or VOI that had been characterized at the time of the study. Vaccine efficacy against cases caused by VOC, among which the Alpha variant was predominant (88.6%), was reported to be 92.6% [[155](#ref-oc5SBo0q)]. In late 2020, an analysis of efficacy in South African adults revealed an overall efficacy of 60.1% and a slightly lower efficacy of 50.1% against B.1.351 in particular [[157](#ref-14K1ANV1T)].

It has also been reported that Novavax initiated booster trials in the U.K. [[72](#ref-wByD9WaX)].

### 0.5.3 Nucleic Acid Vaccines

While traditional methods of vaccine development such as inactivated whole viruses are still used today (Figure [2](#fig:vaccines)), biomedical research in the 21st century has been significantly influenced by the genomic revolution, and vaccine development is no exception. The shift towards omics-based approaches to vaccine development began to take hold with the development of the meningococcal type B vaccine using reverse vaccinology in the early 2010s [[158](#ref-MCZBJ5sF),[159](#ref-fw8IwtHq)]. In this way, the genomic revolution catalyzed a fundamental shift in the development of vaccines. These vaccine technologies could potentially provide a future approach to addressing one of the major limitations of vaccines today due to their potential to function therapeutically rather than just prophylactically [[160](#ref-kqerKJKY)].

Nucleic-acid based approaches are all based on the shared underlying principle that utilizing a vector to deliver the information to produce an antigen can trigger an immune response to the antigen without introducing an infectious agent. Such approaches build on subunit vaccination strategies, where a component of a vaccine (e.g., an antigenic protein) is delivered. Platforms based on genomic sequencing began to be explored beginning in the 1980s as genetic research became increasingly feasible. Advances in genetic engineering allowed for gene sequences of specific viral antigens to be grown *in vitro* [[1](#ref-YY3x3bBV)]. Studies also demonstrated that model organisms could be induced to construct antigens that would trigger an immune response [[40](#ref-U9ZIZWkB),[161](#ref-pWMIo6pD),[162](#ref-uPszIvSj)]. These two developments meant that it could be possible to identify any or all of the antigens encoded by a virus’s genome and train the immune response to recognize them. In nucleic-acid-based approaches, the genome of a pathogen is screened to identify potential vaccine targets [[159](#ref-fw8IwtHq)], and pathogens of interest are then expressed *in vitro* and tested in animal models to determine their immunogenicity [[159](#ref-fw8IwtHq)]. By inducing the host to express the antigen, such vaccines can activate immune pathways via both MHC I and MHC II [[163](#ref-fwumPoq1)] instead of MHC II alone as with prior technologies [[162](#ref-uPszIvSj)], meaning that both humoral and cellular immunity are activated [[8](#ref-BsrTDzJ2)]. Thus, in addition to lacking an infectious agent, these approaches are likely to offer several advantages over more traditional immunization platforms because they can stimulate both B- and T-cell responses [[8](#ref-BsrTDzJ2),[164](#ref-29LxSWHB)].

The delivery and presentation of antigens is fundamental to inducing immunity against a virus. Vaccines that deliver nucleic acids allow the introduction of foreign substances to the body to induce both humoral and cellular immune responses [[8](#ref-BsrTDzJ2)]. Delivering a nucleic acid sequence to host cells allows the host to synthesize an antigen without exposure to a viral threat [[8](#ref-BsrTDzJ2)]. Host-synthesized antigens can then be presented in complex with major histocompatibility complex (MHC) I and II, which can activate either T- or B-cells [[8](#ref-BsrTDzJ2)]. While these vaccines encode specific proteins, providing many of the benefits of a protein subunit vaccine, they do not carry any risk of DNA being live, replicating, or spreading, and their manufacturing process lends itself to scalability [[8](#ref-BsrTDzJ2)]. Here, opportunities can be framed in terms of the central dogma of genetics: instead of directly providing the proteins from the infectious agents, vaccines developers are exploring the potential for the delivery of DNA or RNA to induce the cell to produce proteins from the virus that in turn induce a host immune response.

#### 0.5.3.1 DNA Vaccines

Nucleic acid information can be deliver antigen information to host cells using DNA. However, early attempts to use these technologies to develop vaccines revealed that DNA translated poorly to humans due to low immunogenicity [[40](#ref-U9ZIZWkB),[162](#ref-uPszIvSj),[165](#ref-12jFcMeQY)]. Initially, concerns were raised that DNA vaccines might bind to the host genome or induce autoimmune disease [[8](#ref-BsrTDzJ2),[163](#ref-fwumPoq1)], but pre-clinical and clinical studies have consistently disproved this hypothesis and indicated DNA vaccines to be safe [[165](#ref-12jFcMeQY)]. Many of the safety concerns raised about DNA vaccines were not found to be an issue during preclinical and phase I testing, although antibiotic resistance introduced during the plasmid selection process remained a concern during this initial phase of development [[8](#ref-BsrTDzJ2)]. However, the immunogenicity of these vaccines has also not reached expectations [[8](#ref-BsrTDzJ2)]. Despite initially disappointing immunogenicity in clinical trials [[162](#ref-uPszIvSj)], a number of developments during the 2010s led to greater efficacy of DNA vaccines [[8](#ref-BsrTDzJ2)]. However, no DNA vaccines had been approved for use in humans prior to the COVID-19 pandemic [[165](#ref-12jFcMeQY),[166](#ref-yriARFOF)].

Table 3: Approved DNA vaccines [[41](#ref-jswAyWIs)]

| Vaccine | Company | Platform |
| --- | --- | --- |
| Convidecia | CanSino | non replicating viral vector |
| Gam-COVID-Vac | Gamaleya | non replicating viral vector |
| Sputnik Light | Gamaleya | non replicating viral vector |
| Sputnik V | Gamaleya | non replicating viral vector |
| Ad26.COV2.S | Janssen (Johnson & Johnson) | non replicating viral vector |
| Vaxzevria | Oxford/AstraZeneca | non replicating viral vector |
| Covishield (Oxford/ AstraZeneca formulation) | Serum Institute of India | non replicating viral vector |
| ZyCoV-D | Zydus Cadila | plasmid vectored |

#### 0.5.3.2 Plasmid-Vectored DNA Vaccines

**Mechanism:** Many DNA vaccines use a plasmid vector-based approach, where the sequence encoding the antigen(s) against which an immune response is sought can be cultivated in a plasmid and delivered directly to an appropriate tissue [[167](#ref-XnrBoKVk)]. Plasmids can also be designed to act as adjuvants by encoding molecules that supplement the immune response, such as immune stimulant molecules [[163](#ref-fwumPoq1)]. The DNA itself may also stimulate the innate immune response [[162](#ref-uPszIvSj)]. Once the plasmid brings the DNA sequence to an APC, the host machinery can be used to construct antigen(s) from the transported genetic material, and the body can then synthesize antibodies in response [[8](#ref-BsrTDzJ2)]. In the 1990s and 2000s, DNA vaccines delivered via plasmids sparked significant scientific interest, leading to a large number of preclinical trials [[8](#ref-BsrTDzJ2)].

**Prior Applications:** Early preclinical trials primarily focused on long-standing disease threats, including viral diseases such as rabies and bacterial diseases such as malaria, and promising results led to phase I testing of the application of this technology to HIV, influenza, malaria, and other diseases of concern during this period [[8](#ref-BsrTDzJ2)]. Although they were well-tolerated, these early attempts to develop vaccines were generally not very successful in inducing immunity to the target pathogen, with either limited T-cell or limited neutralizing antibody responses observed [[8](#ref-BsrTDzJ2)].

**Applications to COVID-19:** Currently, a Phase I safety and immunogenicity clinical trial of INO-4800, a prophylactic vaccine against SARS-CoV-2, is underway [[168](#ref-xuzLfS0y)]. The vaccine developer Inovio Pharmaceuticals Technology is overseeing administration of INO-4800 by intradermal injection followed by electroporation with the CELLECTRA® device to healthy volunteers. Electroporation is the application of brief electric pulses to tissues in order to permeabilize cell membranes in a transient and reversible manner. It has been shown that electroporation can enhance vaccine efficacy by up to 100-fold, as measured by increases in antigen-specific antibody titers [[169](#ref-H6tWVs5R)]. The safety of the CELLECTRA® device has been studied for over seven years, and these studies support the further development of electroporation as a safe vaccine delivery method [[170](#ref-1Hsm2J1sc)]. The temporary formation of pores through electroporation facilitates the successful transportation of macromolecules into cells, allowing cells to robustly take up INO-4800 for the production of an antibody response. Approved by the United States (U.S.) FDA on April 6, 2020, the phase I study is enrolling up to 40 healthy adult volunteers in Philadelphia, PA at the Perelman School of Medicine and at the Center for Pharmaceutical Research in Kansas City, MO. The trial has two experimental arms corresponding to the two locations. Participants in Experimental Group 1 will receive one intradermal injection of 1.0 milligram (mg) of INO-4800 followed by electroporation using the CELLECTRA® 2000 device twice, administered at Day 0 and Week 4. Participants in Experimental Group 2 will receive two intradermal injections of 1.0 mg (total 2.0 mg per dosing visit) of INO-4800 followed by electroporation using the CELLECTRA® 2000 device, administered at Day 0 and Week 4. Safety data and the initial immune responses of participants from the trial are expected by the end of the summer of 2021. The development of a DNA vaccine against SARS-CoV-2 by Inovio could be an important step forward in the world’s search for a COVID-19 vaccine. Although exciting, the cost of vaccine manufacturing and electroporation may make scaling the use of this technology for prophylactic use for the general public difficult.

#### 0.5.3.3 Viral-Vectored DNA Vaccines

**Mechanism:** Plasmids are not the only vector that can be used to deliver sequences associated with viral antigens: genetic material from the target virus can also be delivered using a second virus as a vector. Viral vectors have emerged as a safe and efficient method to furnish the nucleotide sequences of an antigen to the immune system using a second virus as a vector [[171](#ref-1Ff2BDzkT)]. The genetic content of the vector virus is often altered to prevent it from replicating, but replication-competent viruses can also be used under certain circumstances [[172](#ref-1FpZkxdl4)]. Once the plasmid or viral vector brings the DNA sequence to an APC, the host machinery can be used to construct antigen(s) from the transported genetic material, and the body can then synthesize antibodies in response [[8](#ref-BsrTDzJ2)]. These vaccines can be either replicating or non-replicating [[54](#ref-bgKUtUIL)]. One of the early viral vectors explored was adenovirus, with serotype 5 (Ad5) being particularly effective [[8](#ref-BsrTDzJ2)]. This technology rose in popularity during the 2000s due to its being more immunogenic in humans and non-human primates than plasmid-vectored DNA vaccines [[8](#ref-BsrTDzJ2)]. In the 2000s, interest also arose in utilizing simian adenoviruses as vectors because of the reduced risk that human vaccine recipients would have prior exposure resulting in adaptive immunity [[8](#ref-BsrTDzJ2),[173](#ref-XRmk1S6R)], and chimpanzee adenoviruses were explored as a potential vector in the development of a vaccine against *Middle East respiratory syndrome-related coronavirus* (MERS-CoV) [[174](#ref-Jkm7jfS8)]. Today, various viral-vector platforms including poxviruses [[175](#ref-8bpbvIro),[176](#ref-1AZfAQ5py)], adenoviruses [[177](#ref-zX5UKhti)], and vesicular stomatitis viruses [[178](#ref-SNwg8Qkf),[179](#ref-lvi4DH2g)] are being developed, Viral-vector vaccines are able to induce both an antibody and cellular response; however, the response is limited due to the immunogenicity of the viral vector used [[177](#ref-zX5UKhti),[180](#ref-YRgRziXN)]. An important consideration in identifying potential vectors is the immune response to the vector. Both the innate and adaptive immune responses can potentially respond to the vector, limiting the ability of the vaccine to transfer information to the immune system [[181](#ref-tbs2wD7F)]. Different vectors are associated with different levels of reactogenicity; for example, adenoviruses elicit a much stronger innate immune response than replication deficient adeno-associated viruses derived from parvoviruses [[181](#ref-tbs2wD7F)]. Additionally, using a virus circulating widely in human populations as a vector presents additional challenges because vaccine recipients may already have developed an immune response to the vector [[182](#ref-IUplTKEg)].

**Prior Applications:** There are several viral vector vaccines that are available for veterinary use [[8](#ref-BsrTDzJ2),[183](#ref-MvKb0qJC)], but prior to the COVID-19 pandemic, only one viral vector vaccine was approved by the FDA for use in humans. This vaccine is vectored with a recombinant vesicular stomatitis virus and targeted against the ebola virus [[184](#ref-9g5tmszW)]. Additionally, several phase I and phase II clinical trials for other vaccines are ongoing [[171](#ref-1Ff2BDzkT)], and the technology is currently being explored for its potential against numerous infectious diseases including malaria [[185](#ref-OZJWUaDW),[186](#ref-3tkGuMXx)], ebola [[187](#ref-AgZwwt5u),[188](#ref-9BEMTYn8),[189](#ref-PbGQOOI)], and human immunodeficiency virus (HIV) [[190](#ref-1C8hgfvDF),[191](#ref-SAIfGNkZ)]. The threat of MERS and SARS initiated interest in the application of viral vector vaccines to human coronaviruses [[174](#ref-Jkm7jfS8)], but efforts to apply this technology to these pathogens had not yet led to a successful vaccine candidate. In the mid-to-late 00s, adenoviral vectored vaccines against SARS were found to induce SARS-CoV-specific IgA in the lungs of mice [[192](#ref-umEOWDY5)], but were later found to offer incomplete protection in ferret models [[193](#ref-DGTFML2b)]. Gamaleya National Center of Epidemiology and Microbiology in Moscow sought to use an adenovirus platform for the development of vaccines for *Middle East respiratory syndrome-related coronavirus* and Ebola virus, although neither of the previous vaccines were internationally licensed [[194](#ref-UCI0TCHy)].

In 2017, results were published from an initial investigation of two vaccine candidates against MERS-CoV containing the MERS-CoV S gene vectored with chimpanzee adenovirus, Oxford University #1 (ChAdOx1), a replication-deficient chimpanzee adenovirus [[195](#ref-P94sxWp4)]. This study reported that a candidate containing the complete spike protein sequence induced a stronger neutralizing antibody response in mice than candidates vectored with modified vaccinia virus Ankara. It was pursued in additional research, and in the summer of 2020 results of two studies were published. The first reported that a single dose of ChAdOx1 MERS induced an immune response and inhibited viral replication in macaques [[196](#ref-3NtMBDMM)]. The second reported promising results from a phase I trial that administered the vaccine to adults and measured safety/tolerability and immune response (as indicated through immune assays following vaccination) [[197](#ref-ERfSJf5B)].

**Application to COVID-19:** While not all of these results were available at the time that vaccine development programs against SARS-CoV-2 began, at least three viral vector vaccines have also been developed against this hCoV. First, collaboration between AstraZeneca and researchers at the University of Oxford has successfully applied a viral vector approach to the development of a vaccine against SARS-CoV-2 using the replication-deficient ChAdOx1 vector modified to encode the spike protein of SARS-CoV-2 [[198](#ref-1037p4Gvs)]. In phase I and I/II trials, respectively, the immunogenic potential of vaccine candidate ChAdOx1 nCoV-19 was demonstrated through the immune challenge of two animal models, mice and rhesus macaques [[198](#ref-1037p4Gvs)] and patients receiving the ChAdOx1 nCoV-19 vaccine developed antibodies to the SARS-CoV-2 spike protein that peaked by day 28, with these levels remaining stable until a second observation at day 56 [[199](#ref-2bBVSpM)].

Second, a viral vector approach was also applied by Gamaleya to develop Sputnik V, a replication-deficient recombinant adenovirus (rAd) vaccine that combines two adenovirus vectors, rAd26-S and rAd5-S, that express the full-length SARS-CoV-2 spike glycoprotein. The two vectors are administered intramuscularly administered sequentially, following a prime-boost regimen. Despite a lack of data from clinical trials, President Vladimir Putin of Russia announced the approval of the Sputnik V vaccines on August 11th, 2020 [[200](#ref-3KMxmQhV)] and it has subsequently been administered in Russia and other countries.

Third, Janssen Pharmaceuticals, Inc., a subsidiary of Johnson & Johnson, also developed a viral vector vaccine in collaboration with and funded by the United States’s “Operation Warp Speed” [[201](#ref-D3Px25HN),[202](#ref-57BTbcko)]. The vaccine candidate JNJ-78436735, formerly known as Ad26.COV2-S, is a monovalent vaccine that is composed of a replication-deficient adenovirus serotype 26 (Ad26) vector expressing the stabilized prefusion S protein of SARS-CoV-2 [[28](#ref-10UC562ga),[203](#ref-pWf2T8J8)]. Unlike the other two viral vector vaccines available to date, JNJ-78436735 requires only a single dose, a characteristic that is expected to aid in global deployment [[204](#ref-gOOBv1MD)]. JNJ-78436735 was selected from among a number of initial candidate designs [[28](#ref-10UC562ga)] and tested *in vivo* in Syrian golden hamsters and Rhesus macaques to assess safety and immunogenicity [[28](#ref-10UC562ga),[204](#ref-gOOBv1MD),[205](#ref-HmMIiIv2),[206](#ref-EpOXYGt4)]. The JNJ-78436735 candidate was selected for its favorable immunogenicity profile and ease of manufacturability [[28](#ref-10UC562ga),[204](#ref-gOOBv1MD),[205](#ref-HmMIiIv2),[206](#ref-EpOXYGt4)] and was found to confer protection against SARS-CoV-2 in macaques even after six months [[207](#ref-HGVDPMLm)]. The one- versus two-dose regimen was tested in volunteers through a phase I/IIa trial [[203](#ref-pWf2T8J8)], although these results are not yet available; however, the study did report that the vaccine was well-tolerated and that most participants demonstrated seroconversion in a neutralization assay 29 days after immunization [[203](#ref-pWf2T8J8)].

The three viral-vector vaccines described above have demonstrated the potential for this technology to facilitate a quick response to an emerging pathogen. Additionally, though the vaccines are developed using similar principles, there are some differences that might influence their efficacy as SARS-CoV-2 evolves. In the Janssen vaccine, the S protein immunogen is stabilized in its prefusion conformation, while in the Sputnik V and AstraZeneca vaccines, it is not. How these differences in design influence the efficacy of these three viral-vector vaccines over time remains to be seen.

**Efficacy Estimates:** The first DNA viral-vectored vaccine for which efficacy estimates became available was AstraZeneca’s ChAdOx1 nCoV-19. In December 2020, preliminary results of the phase III trial were released detailing randomized control trials conducted in the U.K., Brazil, and South Africa between April and November 2020 [[12](#ref-Vnbw9o3T)]. These trials again compared ChAdOx1 nCoV-19 to a control, but the design of each study varied; pooling data across studies indicated an overall efficacy of 70.4%.

For Sputnik V, the phase III trial indicated an overall vaccine efficacy of 91.6% for symptomatic COVID-19 [[208](#ref-gLAIyAHm)].

As for Janssen, the phase III trial is ongoing across several countries (Argentina, Brazil, Chile, Colombia, Mexico, Peru, South Africa, and the U.S.), but interim results were reported in a press release on January 29th, 2021 [[209](#ref-iWMHpTBJ),[210](#ref-1FcpboRMm)]. The vaccine was well-tolerated, and across all regions studied, it was found to be 66% effective after 28 days for the prevention of moderate to severe COVID-19 and to be 85% effective for the prevention of laboratory-confirmed severe COVID-19 as well as 100% protection against COVID-19-related hospitalization and death.

**Distribution Status:** As of April 21, 2022, 7 viral-vectored vaccines are being distributed in 201 countries (Figure [5](#fig:nrvv-distrib)). ChAdOx1 nCoV-19 was first approved for emergency use on December 30, 2020 in the United Kingdom [[211](#ref-1A7PjhDDR)] and has since then been approved for emergency use in several dozen countries, in addition to receiving full approval in Brazil.



Figure 5: **Worldwide availability of vaccines developed using non-replicating viral vectors.** This figure reflects the number of vaccines using non-replicating viral vectors that were available in each country as of April 21, 2022. These data are retrieved from Our World in Data <!-To Do: Cite–> and plotted using geopandas. See https://greenelab.github.io/covid19-review/ for the most recent version of this figure, which is updated daily.

As of early January, Sputnik V had been administered to as many as 1.5 million Russians [[212](#ref-X5LkVfY6)], and doses of Sputnik V have also been distributed to other parts of Europe, such as Belarus, Bosnia-Herzegovina, Hungary, San Marino, Serbia, and Slovakia [[213](#ref-16LczMwFO),[214](#ref-Z0V7NK7Y),[215](#ref-16GYKbrOq)], with the Czech Republic and Austria also having expressed interest in its procurement [[216](#ref-125VEHWS7)]. It wasn’t until February 2021, six months after its approval in Russia, that interim results of the phase III trial were released [[208](#ref-gLAIyAHm)].

However, two of the three vaccines have faced a number of criticisms surrounding the implementation of their clinical trials.

**Variants:** A range of efficacy estimates were reported for Janssen’s vaccine candidate, with estimates varying from 57% in South Africa to 72% in the United States. These differences suggested that efficacy might be influenced by the prominent viral strains circulating in each country at the time of the trial, since at the time, several variants of concern were being monitored, including B.1.351, which was first identified in South Africa [[217](#ref-sqhvCTIL)].

#### 0.5.3.4 RNA Vaccines

Table 4: Approved RNA vaccines [[41](#ref-jswAyWIs)]

| Vaccine | Company |
| --- | --- |
| Spikevax | Moderna |
| Comirnaty | Pfizer/BioNTech |
| TAK-919 (Moderna formulation) | Takeda |

**Mechanism:** Building on DNA vaccine technology, RNA vaccines are an even more recent advancement for vaccine development. Interest in messenger RNA (mRNA) vaccines emerged around 1990 following *in vitro* and animal model studies that demonstrated that mRNA could be transferred into cells [[218](#ref-D7ou3S22),[219](#ref-2YZ70C2y)]. mRNA contains the minimum information needed to create a protein [[219](#ref-2YZ70C2y)]. RNA vaccines are therefore nucleic-acid based modalities that code for viral antigens against which the human body elicits a humoral and cellular immune response. This approach operates one level above the DNA: instead of directly furnishing the gene sequence associated with an antigen to the host, it provides the mRNA transcribed from the DNA sequence. Some of the potential advantages of mRNA compared to DNA include safety, as it cannot be integrated by the host and the half life can be regulated, it avoids any issues of a host immune response against the vector, and it holds the potential to dramatically accelerate vaccine manufacturing and development [[219](#ref-2YZ70C2y),[220](#ref-ENBWnhAh)].

The mRNA technology is transcribed *in vitro* and delivered to cells via lipid nanoparticles (LNP) [[221](#ref-HCImhzy8)]. They are recognized by ribosomes *in vivo* and then translated and modified into functional proteins [[39](#ref-K0Ltu31S)]. The resulting intracellular viral proteins are displayed on surface MHC proteins, provoking a strong CD8+ T cell response as well as a CD4+ T cell and B cell-associated antibody responses [[39](#ref-K0Ltu31S)]. Naturally, mRNA is not very stable and can degrade quickly in the extracellular environment or the cytoplasm. The LNP covering protects the mRNA from enzymatic degradation outside of the cell [[222](#ref-zNKWlCwE)]. Codon optimization to prevent secondary structure formation and modifications of the poly-A tail as well as the 5’ untranslated region to promote ribosomal complex binding can increase mRNA expression in cells. Furthermore, purifying out double-stranded RNA and immature RNA with FPLC (fast performance liquid chromatography) and HPLC (high performance liquid chromatography) technology will improve translation of the mRNA in the cell [[39](#ref-K0Ltu31S),[223](#ref-pRoqjur8)].

There are three types of RNA vaccines: non-replicating, *in vivo* self-replicating, and *in vitro* dendritic cell non-replicating [[224](#ref-1EM5nGaYd)]. Non-replicating mRNA vaccines consist of a simple open reading frame (ORF) for the viral antigen flanked by the 5’ UTR and 3’ poly-A tail. *In vivo* self-replicating vaccines encode a modified viral genome derived from single-stranded, positive sense RNA alphaviruses [[39](#ref-K0Ltu31S),[223](#ref-pRoqjur8)]. The RNA genome encodes the viral antigen along with proteins of the genome replication machinery, including an RNA polymerase. Structural proteins required for viral assembly are not included in the engineered genome [[39](#ref-K0Ltu31S)]. Self-replicating vaccines produce more viral antigens over a longer period of time, thereby evoking a more robust immune response [[224](#ref-1EM5nGaYd)]. Finally, *in vitro* dendritic cell non-replicating RNA vaccines limit transfection to dendritic cells. Dendritic cells are potent antigen-presenting immune cells that easily take up mRNA and present fragments of the translated peptide on their MHC proteins, which can then interact with T cell receptors. Ultimately, primed T follicular helper cells can stimulate germinal center B cells that also present the viral antigen to produce antibodies against the virus [[225](#ref-3LMMW7F0)]. These cells are isolated from the patient, grown and transfected *ex vivo*, and reintroduced to the patient [[220](#ref-ENBWnhAh)].

Vaccines based on mRNA delivery confer many advantages over traditional viral vectored vaccines and DNA vaccines. In comparison to live attenuated viruses, mRNA vaccines are non-infectious and can be synthetically produced in an egg-free, cell-free environment, thereby reducing the risk of a detrimental immune response in the host [[226](#ref-wYZ6qJMu)]. Unlike DNA vaccines, mRNA technologies are naturally degradable and non-integrating, and they do not need to cross the nuclear membrane in addition to the plasma membrane for their effects to be seen [[39](#ref-K0Ltu31S)]. Furthermore, mRNA vaccines are easily, affordably, and rapidly scalable. Although mRNA vaccines have been developed for therapeutic and prophylactic purposes, none have previously been licensed or commercialized. Nevertheless, they have shown promise in animal models and preliminary clinical trials for several indications, including rabies, coronavirus, influenza, and cytomegalovirus [[227](#ref-3EUiWZdN)]. Preclinical data previously identified effective antibody generation against full-length FPLC-purified influenza hemagglutinin stalk-encoding mRNA in mice, rabbits, and ferrets [[228](#ref-6wZy2mn8)]. Similar immunological responses for mRNA vaccines were observed in humans in Phase I and II clinical trials operated by the pharmaceutical-development companies Curevac and Moderna for rabies, flu, and zika [[223](#ref-pRoqjur8)]. Positively charged bilayer LNPs carrying the mRNA attract negatively charged cell membranes, endocytose into the cytoplasm [[222](#ref-zNKWlCwE)], and facilitate endosomal escape. LNPs can be coated with modalities recognized and engulfed by specific cell types, and LNPs that are 150 nm or less effectively enter into lymphatic vessels [[222](#ref-zNKWlCwE),[229](#ref-Djz8x39x)]. Therefore, this technology holds great potential for targeted delivery of modified mRNA.

**Prior Applications:** mRNA vaccine technology was even slower to develop due to challenges related to the instability of mRNA molecules, the design requirements of an efficient delivery system, and the potential for mRNA to elicit either a very strong immune response or to stimulate the immune system in secondary ways [[160](#ref-kqerKJKY),[230](#ref-17lluDFcc)]. As of the 2010s, mRNA was still considered a promising technology for future advances in vaccine development [[219](#ref-2YZ70C2y)], but prior to 2020, no mRNA vaccines had been approved for use in humans, despite significant advances in the development of this technology [[220](#ref-ENBWnhAh)]. Therefore, while these technologies elegantly capitalize on decades of research in vaccine development as well as the tools of the genomic revolution, it was largely unknown prior to the SARS-CoV-2 pandemic whether this potential could be realized in a real-world vaccination effort.

**Application to COVID-19:** Given the potential for this technology to be quickly adapted for a new pathogen, it was favored as a potential vaccine against COVID-19. In the vaccines developed under this approach, the mRNA coding for a stabilized prefusion spike protein, which is immunogenic [[231](#ref-5x25saIz)], can be furnished to the immune system in order to train its response. Two vaccine candidates in this category emerged with promising phase III results at the end of 2020. Both require two doses approximately one month apart. The first was Pfizer/BioNTech’s BNT162b2, which contains the full prefusion stabilized, membrane-anchored SARS-CoV-2 spike protein in a vaccine formulation based on modified mRNA (modRNA) technology [[232](#ref-1CsCQi9wT),[233](#ref-10VyxCgQU)]. The second mRNA vaccine, mRNA-1273 developed by ModernaTX, is comprised by a conventional lipid nanoparticle encapsulated RNA encoding a full-length prefusion stabilized S protein for SARS-CoV-2 [[234](#ref-Biu1CQeQ)]. As of April 21, 2022, 3 mRNA vaccines are available in 163 countries (Figure [6](#fig:mRNA-distrib)).

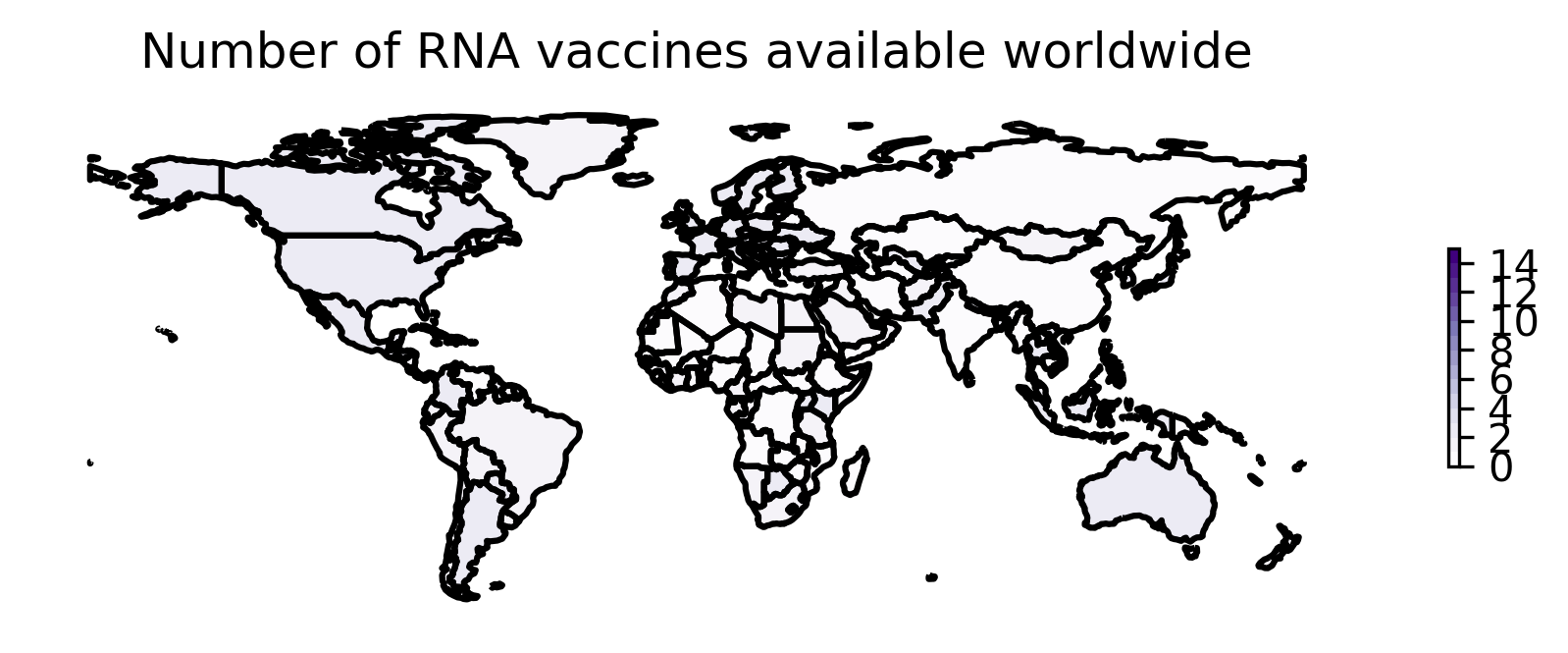


Figure 6: **Worldwide availability of vaccines developed using mRNA.** This figure reflects the number of vaccines based on mRNA technology that were available in each country as of April 21, 2022. These data are retrieved from Our World in Data <!-To Do: Cite–> and plotted using geopandas. See https://greenelab.github.io/covid19-review/ for the most recent version of this figure, which is updated daily.

**Efficacy Estimates:** Pfizer/BioNTech’s BNT162b2 vaccine and ModernaTX’s mRNA-1273 vaccine, commercially known as Comirnaty and Spikevax, are available in most countries thanks to their rapid development in 2020. In a phase II/III multinational trial, the Pfizer/BioNTech’s BNT162b2 vaccine was associated with a 95% efficacy against laboratory-confirmed COVID-19 and with mild-to-moderate local and systemic effects but a low risk of serious adverse effects when the prime-boost doses were administered 21 days apart [[235](#ref-CWlYjjIV)]. The ModernaTX mRNA-1273 vaccine was the second mRNA vaccine to release phase III results, despite being the first mRNA vaccine to enter phase I clinical trials and publish interim results of their phase III trial a few months later. Their study reported a 94.5% vaccine efficacy in preventing symptomatic COVID-19 in adults who received the vaccine at 99 sites around the United States [[236](#ref-ZYxoabEm)]. Similar to BNT162b2, the mRNA-1273 vaccine was associated with mild-to-moderate adverse effects but with a low risk of serious adverse events [[236](#ref-ZYxoabEm)]. Extended details of the initial phase I, II, and III trials for both vaccines are documented in the appendix.

In late 2020, both vaccines received approval from the United States’s Food and Drug Administration (FDA) under an emergency use authorization [[237](#ref-cAaN4Te0),[238](#ref-13Ou1UUAd)], and these vaccines have been widely distributed, primarily in North America and the European Union [[72](#ref-wByD9WaX)]. As the first mRNA vaccines to make it to market, these two highly efficacious vaccines demonstrate the power of this emerging technology, which has previously attracted scientific interest because of its potential to be used to treat non-infectious as well as infectious diseases.

Between December 2020 and April 2021, one prospective cohort study obtained weekly nasal swabs from 3,975 individuals at high risk of SARS-CoV-2 exposure (health care workers, frontline workers, etc.) within the United States [[239](#ref-D2ZCK63Y)]. Among these participants, 3,179 (80%) had received at least one dose of an mRNA vaccine and 2,686 (84%) were fully vaccinated. For each vaccinated participant (defined here as having received at least dose 1 more than 7 days ago) whose sample tested positive for SARS-CoV-2, they categorized the viral lineage(s) present in the sample as well as in samples from 3-4 unvaccinated individuals matched by site and testing date. Overall efficacy of mRNA vaccines was estimated at 91% with full vaccination, similar to the reports from the clinical trials. The occurrence of fevers was also lower in individuals who were partially or fully vaccinated, and the duration of symptoms was approximately 6 days shorter.

Just like the other available COVID-19 vaccines, the efficacy of mRNA vaccines has been challenged by the emergence of variants of concern (VOC). These VOC have gene mutations that code for an altered spike protein, so the antibodies developed resulting from the immunization with the existing vaccines may not be as efficacious, which has caused major concern [[240](#ref-1B4h40dm5),[241](#ref-yqFoGUHl)]. Despite some reports of varying and reduced efficacy of the mRNA vaccines against the Alpha (B.1.1.7), Beta (B.1.351), and Delta (B.1.617.2) variants versus the original SARS-CoV-2 strain or the D614G variant [[[242](#ref-x5yLFKk8)]; [[243](#ref-19dwMfMGe)]; [[244](#ref-63wnlBQD)]; ], the greatest concern to date has been the Omicron variant (B.1.1.529), which was first identified in November 2021 [[241](#ref-yqFoGUHl),[245](#ref-k7L0WGEM)]. As of March 2022, the Omicron variant accounts for 95% of all infections sequenced in the United States [[246](#ref-1Bv67ENp2)] and has been linked to an increased risk of SARS-CoV-2 reinfection [[240](#ref-1B4h40dm5)] and further infection of those who have been vaccinated with the mRNA vaccines [[247](#ref-lexoTbIa)].

Some of the gene mutations carried by Omicron, of which there are between 30-37 in the spike gene (15 in the RBD), have previously been associated with increased transmission, greater affinity for ACE2, and escape from neutralizing antibodies when they have been detected in other VOC [[240](#ref-1B4h40dm5),[241](#ref-yqFoGUHl),[248](#ref-ShwY7D1w),[249](#ref-NdeC7q3I),[249](#ref-NdeC7q3I),[250](#ref-gZ33CJWT)]. However, multiple animal study preprints suggested that the Omicron variant may not be as severe on the respiratory system as previous SARS-CoV-2 variants as evidenced by reduced lung infectivity, reduced SARS-CoV-2 RNA detection in the lung, and reduced inflammation and pathogenicity in animals [[251](#ref-15KUK3sd0),[252](#ref-145MiyjYY),[253](#ref-SV2JRcve),[254](#ref-1HYW5pt3H),[255](#ref-SgbvE4fa)].

In spite of these findings, infection rates and hospitalization rates climbed in early 2022 in many Western countries including the United States [[256](#ref-19qv58Mv3),[257](#ref-TkFSco2t)]. Studies have reported reduced efficacy of the mRNA vaccines based on the measurement of antibody titers. Plasma from individuals double-dosed with Pfizer/BioNTech’s BNT162b2 vaccine had up to a 16-fold reduction in neutralizing capacity against the Omicron variant [[250](#ref-gZ33CJWT)] and a reduced efficacy (70%) [[258](#ref-S6RHdOTJ)]. Estimates for the mRNA vaccines range from a 2-fold to over a 20-fold drop in neutralisation titers [[259](#ref-j172syOP)], hence the push for third doses of mRNA vaccines in many Western countries. A third mRNA vaccine dose does increase antibody titers, but these levels also wane with time [[260](#ref-vJlYzFrS)]. Notably, immunocompromised individuals such as cancer patients seem to elicit a sufficient protective immune response against the Omicron variant when they have been boosted with a third dose of either mRNA vaccine, albeit a blunted response [[261](#ref-sNDCRMQ5)]. While antibody titers do correlate with protection [[262](#ref-J069om3D),[263](#ref-1AtNPSzpd),[264](#ref-QYbPf88B),[265](#ref-1HCZbWd9m),[266](#ref-4WhXhBth)], they are not the only mechanisms of immune protection; for example, T cell and non-neutralizing antibody responses may be unaffected or less affected by the new VOC and they warrant further investigation.

In countries such as Israel, a fourth dose of mRNA vaccines have been introduced in response to the Omicron variant and an initial study in healthcare workers show that the additional immunization is safe and immunogenic with antibody titers restored to peak-third dose titers. No severe illness was reported in the cohort studied (274 versus 426 age-matched controls), and vaccine efficacy against infection was reported at 30% for BNT162b2 and 11% for mRNA-1273 [[267](#ref-Jv71MaZb)]. Low efficacy against infection is not surprising considering the vaccines are intended to prevent against severe disease, hospitalization and death rather than infection.

Vaccine efficacy is not the only pharmacological intervention affected by VOC. Some existing therapeutics, including monoclonal antibody treatments like Bamlanivimab (AbCellera Biologics/ Eli Lilly), were ineffective against the Omicron variant. Indeed, only Sotrovimab (Vir Biotechnology/GSK) and Tixagevimab (AstraZeneca) to a much lesser extent could effectively neutralize the omicron variant out of 7 tested monoclonal antibodies [[250](#ref-gZ33CJWT)], which has been verified by others [[249](#ref-NdeC7q3I)]. The antigenic shift of the Omicron variant does raise concerns for future VOC and what effects they may have on future vaccines and therapeutics.

**Serological Response/Boosters:**

**Variants:**

## 0.6 Vaccine Safety Profiles

The most common adverse reactions reported across all platforms are local site injection pain, redness and swelling and systemic reactions of fever.

| Technology | Platform | Size of Safety Population (N) | Local Adverse Reactions | Systemic Adverse Reactions | Severe Adverse Events | Notes |
| --- | --- | --- | --- | --- | --- | --- |
| IWV | CoronaVac [[66](#ref-Ozya5HP5)] | ? Older Adults | pain (9%) | fever (3%) | 2% |  |
| IWV | CoronaVac [[68](#ref-N1txjPtt)] | 372 adults ages 18-59 | Pain (13-21%) |  | Up to 1 |  |
| IWV | COVAXIN |  |  |  |  |  |
| IWV | SinoPharm [[81](#ref-fPGgVKYL)] | 482 | N/A | N/A |  | 23% reported any AE |
| IWV | WIV04 [[75](#ref-T3MYavsH),[85](#ref-yN5KOfvE)]] |  |  |  | 0.5% | 40-45% of individuals reported mild to moderate side effects 7 days post immunization. Briefly halted due to a death determined to be unrelated [[84](#ref-nxEJTLGU)] |
| Protein Subunit | NVX-CoV2373 [[150](#ref-1D0f8OrG8)] | 2,310 |  | headache, muscle pain, fatigue |  |  |
| DNA | ChAdOx1 nCoV-19 |  |  |  |  |  |
| DNA | Sputnik V [[268](#ref-PNZEiId1)] |  | pain (58%) |  | hypothermia (50%), headaches (42%), fatigue (28%), joint & muscle pain (24%) |  |
| DNA | JNJ-78436735 |  |  |  |  |  |
| mRNA | BNT162b2 |  |  |  |  |  |
| mRNA | mRNA-1273 [[236](#ref-ZYxoabEm)] |  |  |  |  |  |

Several trials have faced pauses while adverse events were investigated. In most cases, these events were determined not to be related to the vaccine.

## 0.7 Efficacy Estimates

Efficacy estimates have been released for many vaccine candidates across a number of technology types. However, efficacy is not a static value, and real-world efficacy can vary with location and over time. Temporal shifts in efficacy have been a especially heightened topic of concern in late 2021 given the potential for the evolution of SARS-CoV-2 to influence vaccine efficacy. The original efficacy estimates are outlined in Table XX and additional considerations for each vaccine type are described in more detail below.

Technology | Platform | Size of Efficacy Population (N) | Estimated Efficacy | Source |  
Whole-virus | CoronaVac | 10,214 (~2:1 vaccine:placebo) | 83.5% | [[70](#ref-1FF7JOwSH)] |  
Whole-virus | COVAXIN | 25,798 (~1:1 vaccine:placebo) | 77.8% | [[86](#ref-n7BupOQ6)] |  
Whole-virus | BBIBP-CorV |  
Whole-virus | Sinopharm | | 79% | [[269](#ref-KXmG3W6c)] |

## 0.8 Special Populations

CoronaVac appears to be suitable for use in immunocompromised patients such as those with autoimmune rheumatic diseases according to phase IV trials [[270](#ref-8vzglCry)]. CoronaVac was also well tolerated and induced humoral responses in phase I trials in children aged 3 to 17 years, which will now be examined in phase II and III clinical trials [[271](#ref-6EYqf6s7)].

## 0.9 Effect of Vaccines on Community Spread

The vaccine clinical trial data demonstrate a significant reduction in the likelihood of contracting symptomatic COVID-19, thereby succeeding in the primary goal of vaccination. The mRNA vaccines in particular are so effective in preventing severe disease and death that it is also worth considering whether they might reduce disease transmission, given that vaccination rates are unlikely to reach 100%. This question hinges on whether vaccinated individuals with or without symptoms of COVID-19 can still spread SARS-CoV-2. This question is made up of several components. The crux is whether vaccinated individuals with a SARS-CoV-2 infection, regardless of symptom status, are as contagious as unvaccinated, infected individuals. Additionally, as outlined above, an important qualification is that the variants of SARS-CoV-2 circulating at the time of each study must be considered in light of the effect of evolution on vaccine efficacy.

The phase 2/3 clinical trials evaluating the mRNA vaccines assessed vaccine efficacy based on COVID-19 diagnosis, thereby detecting only patients who received a diagnosis. In order to identify patients infected with SARS-CoV-2 who did not receive a diagnosis, for example, potentially those who did not develop symptoms, it would be necessary to conduct routine PCR testing even in the absence of symptoms. Prior to the development of vaccines, the evidence suggested that asymptomatic individuals could still spread SARS-CoV-2. Investigation of viral dynamics of asymptomatic infection in early 2020 indicated that asymptomatic patients continued to shed the virus for a duration similar to that of symptomatic patients [[272](#ref-ZU1ZF4SW)] (although viral shedding should not be conflated with contagiousness without further investigation [[9](#ref-GdZc4Yyd)]). Another study found viral load to be higher in the nasopharyngeal/oropharyngeal samples of asymptomatic patients compared to symptomatic patients hospitalized due to symptoms and/or known exposure [[273](#ref-whGzxrkn)]. However, the sample size in both of these studies was small, and a larger study found higher viral load in symptomatic than asymptomatic cases [[274](#ref-34wAjHW5)] along with a systematic review finding a reduced probability of asymptomatic transmission [[275](#ref-1CA0Sj7dn)]. While far from conclusive, these studies suggest that asymptomatic cases still cary a risk of transmitting SARS-CoV-2.

One important consideration is therefore how likely vaccinated individuals are to develop asymptomatic SARS-CoV-2. Considering asymptomatic cases is necessary to establish a more complete picture of efficacy with respect to spread. Routine testing of healthcare workers in California who had received an mRNA vaccine revealed slightly higher rates of absolute risk for testing positive than those identified in the phase 2/3 trials, although the extent to which asymptomatic infection influenced these numbers was not investigated [[276](#ref-13llzZ2qN)]. Another study analyzed the results of COVID-19 screening tests administered to asymptomatic individuals prior to receiving certain medical services at the Mayo Clinic in several locations across the United States. This study found patients who had received two doses of an mRNA vaccine to be 73% less likely to have asymptomatic COVID-19 than patients who had received zero doses [[277](#ref-dLmXTkx0)]. Because this study began on December 17, 2020, a date selected to coincide with the first day vaccines were available at the Mayo Clinic, this number may underestimate the efficacy of the vaccines given that many people eligible for early vaccination were at increased risk for exposure (e.g., healthcare workers and residents of long-term care facilities) [[277](#ref-dLmXTkx0)]. In Israel, a longitudinal study of nearly 12,000 healthcare workers found that of the 5,372 fully vaccinated people with Pfizer/BioNTech BNT162b2, 8 developed symptomatic COVID-19 (BNT162b2 (.15%) and 19 developed asymptomatic COVID-19 (.35%) [[278](#ref-zHE6Quu6)]. While the study itself analyzed the efficacy of the vaccine based on person-days, these findings also suggest that many or even the majority of SARS-CoV-2 infections in vaccinated individuals are likely to be asymptomatic. Therefore, in addition to the symptomatic cases reported by the vaccine clinical trials, these findings suggest that asymptomatic cases can also occur in vaccinated people. In the absence of symptoms, individuals are less likely to know to self-isolate, and therefore evaluating the effect of the vaccine on viral load is critical to understanding the role vaccinated individuals can play in spreading SARS-CoV-2.

Another question of interest is therefore whether vaccinated individuals positive for SARS-CoV-2 carry a similar viral load to unvaccinated individuals. Viral load is often approximated by cycle threshold (Ct), or the cycle at which viral presence is detected during RT-qPCR, with a lower Ct corresponding to a greater viral load. A prospective cohort study that evaluated front-line workers in six U.S. states from December 2020 to April 2021 reported a 40% reduction in viral load even with just a single dose of an mRNA vaccine [[239](#ref-D2ZCK63Y)]. The vaccine also appeared to influence the time to viral clearance: the risk of having detectable levels of SARS-CoV-2 for more than one week was reduced by 66% in participants who had received at least one dose [[239](#ref-D2ZCK63Y)]. However, this study compared the mean viral load across the two groups, meaning that these findings cannot be extrapolated across all points in the disease course. Similarly, between December 2020 and February 2021, positive RT-qPCR tests were analyzed for almost 5,000 Israeli patients [[279](#ref-119cExL0k)]. Ct was analyzed relative to when each patient received the first dose of the Pfizer mRNA vaccine. A sharp increase in Ct (corresponding to reduced viral load) was observed between days 11 and 12, consistent with what is known about the onset of immunity following vaccination. This pattern therefore suggested a direct effect of vaccination on viral load.

Other studies, however, have not offered support for a reduced viral load in breakthrough cases. In Singapore, which has strict protocols for screening individuals with potential COVID-19 exposure, a retrospective cohort of patients who tested positive for SARS-CoV-2 between April and June 2021 was analyzed to compare viral kinetics and symptom course between vaccinated and unvaccinated cases. Vaccinated individuals who tested positive experienced fewer symptoms than unvaccinated, SARS-CoV-2-positive individuals and were more likely to be asymptomatic [[280](#ref-e2Qnnj6R)] (Appendix). Additionally, this study analyzed Ct over time and found that, though the median values were similar between the two groups at disease onset, viral load appeared to decrease more rapidly in vaccinated cases [[280](#ref-e2Qnnj6R)] (Appendix). This study is likely to have evaluated a more accurate representation of all COVID-19 outcomes than has been feasible in most studies, but one limitation was that the RT-PCR reactions were conducted in many different facilities. A third study investigated viral load (as approximated by Ct) using samples processed in a single laboratory during the summer of 2021 [[281](#ref-N5OXLf7V)]. This study identified no significant differences in Ct between fully vaccinated and unvaccinated cases, but this study used samples sent for diagnosis and was not longitudinal. It offered the additional benefit of culturing samples to assess whether their Ct threshold was likely to represent contagiousness and found that SARS-CoV-2 could be cultured from 51 of 55 samples with Ct less than 25 (the cut-off used in many studies). Another study of samples collected at two sites in San Francisco, one of which tested only asymptomatic individuals, reported no difference in Ct between asymptomatic and symptomatic cases regardless of whether vaccination status was included in the model [[282](#ref-mgscHeDu)]. Though each of these three studies offers distinct strengths and weaknesses, taken together, they suggest that viral load is likely to be similar in vaccinated and unvaccinated individuals, but that vaccinated individuals clear the virus more rapidly, meaning that the average viral load is lower over time.

Given the emergence of variants of concern, especially the Delta variant, for which breakthrough infections are more common, the potential for vaccinated individuals to spread SARS-CoV-2 is not necessarily static over time. In fact, studies reporting reduced viral load in vaccinated individuals collected samples, for the most part, prior to the emergence of the Delta variant’s dominance. The emergence of this variant may partially account for why more recent studies tend to find no difference between viral load in vaccinated and unvaccinated cases.

Taken together, these findings can provide some insight into how vaccines influence community spread. While vaccinated individuals may be more likely to experience asymptomatic infection, current evidence about viral load in asymptomatic versus symptomatic cases is ambiguous. Similarly, no conclusions can be drawn about whether viral load is different in vaccinated versus unvaccinated cases. Therefore, at present, the evidence suggests that vaccinated individuals who are infected can still contribute to community spread. The one potential mitigating factor supported at present is that differences in the viral kinetics may result in vaccinated cases infecting fewer individuals over time due to a more rapid decrease in viral load [[280](#ref-e2Qnnj6R)], although this study did not examine patterns in secondary transmission. Thus, the virological evidence suggests that public health measures such as masking and distancing remain important even in areas with high vaccination rates.

### 0.9.1 Other Concerns in Efficacy

Given the wide range of vaccines under development, it is possible that some vaccine products may eventually be shown to be more effective in certain subpopulations, such as children, pregnant women, immunocompromised patients, the elderly, etc.

Age distribution in clinical trials? https://doi.org/10.1016/j.arr.2021.101455

Concerns: diversity of volunteer pools, variants, and distribution Another benefit of vaccines is lower population size in SARS-CoV-2 = less risk of VOC emerging that are less susceptible to the vaccine

Given the apparent need for boosters, interest has also emerged in whether vaccines against SARS-CoV-2 can be administered along with annual flu vaccines. Early data came from the Novavax NVX-CoV2373 protein subunit vaccine. In a subgroup of approximately 400 patients enrolled from the U.K. phase III trial who received either NVX-CoV2373 or placebo 1:1, a concomitant dose of adjuvanted seasonal influenza vaccines (either a trivalent vaccine or a quadrivalent vaccine) was administered [[283](#ref-IUekaKY0)]. This study demonstrated that both types of vaccines could be safely administered together. While no change to the immune response was noted for the influenza vaccine, a notable reduction of the antibody response for the NVX-CoV2373 was reported, but efficacy was still high at 87.5% [[283](#ref-IUekaKY0)]. Novavax has since started phase I/II trials to investigate the administration of its own influenza vaccine, NanoFlu™, concomitantly with NVX-CoV2373 [[284](#ref-rclKBvtk)], which appeared to be safe and effective in preclinical studies [[285](#ref-bOwPRh6q)].

Indeed, Chinese [[103](#ref-9oJ3sbrk)] and Chilean [[286](#ref-uPt61a0E)] researchers have opted to investigate options to administer different vaccines (e.g., an mRNA vaccine dose) as a booster dose to individuals who have already received two doses of the IWV vaccine CoronaVac. Another study has already determined that using the CanSino vaccine (Convidecia) instead of CoronaVac in a prime-boost vaccination regimen can induce a more robust immune response [[105](#ref-1HVWY0Qmv)].

## 0.10 Conclusions

In the early 2000s, technologies such as inactivated viral vaccines, live attenuated viral vaccines, protein subunit vaccines, and recombinant vector-based vaccines were explored for SARS [[287](#ref-H4USOXie),[288](#ref-AOGjkjCq)], but the epidemic was controlled before these efforts came to fruition [[4](#ref-HyYY2agc)]. DNA vaccine development efforts also began but did not proceed past animal testing [[288](#ref-AOGjkjCq)]. Similarly, viral vector, protein subunit, and DNA vaccines were explored for MERS-CoV, but outbreaks are sporadic and difficult to predict, making vaccine testing and the development of a vaccination strategy difficult [[289](#ref-138O0v19T)]. Likewise, the development of viral-vectored Ebola virus vaccines was undertaken, but the pace of vaccine development was behind the spread of the virus from early on [[290](#ref-vTrIB9zS)]. Although a candidate Ebola vaccine V920 showed promise in preclinical and clinical testing, it did not receive breakthrough therapy designation until the summer of 2016, by which time the Ebola outbreak was winding down [[291](#ref-8uuVgxzA)].

# 1 Vaccine Development Strategies for SARS-CoV-2 Appendix

## 1.1 Live Attenuated Viruses

One candidate in the preclinical stage is YF-S0, a single-dose LAV developed at Katholieke Universiteit Leuven that uses live-attenuated yellow fever 17D (YF17D) as a vector for a noncleavable prefusion conformation of the SARS-CoV-2 antigen. YF-S0 induced a robust immune response in three animal models and prevented SARS-CoV-2 infection in macaques and hamsters [[42](#ref-4RuaSyLg)].

Other programs are exploring the development of codon deoptimized LAV [[46](#ref-nwyfEEPl),[47](#ref-iCUWeMfX),[48](#ref-xMxJTYge)]. New York-based Codagenix and the Serum Institute of India reported a successful preclinical investigation [[48](#ref-xMxJTYge)] of an intranasally administered deoptimized SARS-CoV-2 LAV known as COVI-VAC, and COVI-VAC entered phase I human trials and dosed its first participants in January 2021 [[47](#ref-iCUWeMfX),[292](#ref-bPMpOwp8)]. It is anticipated that the COVI-VAC phase I human trials will be completed by May 2022.

Another company, Meissa Vaccines in Kansas, U.S.A., which also develops vaccines for Respiratory syncytial virus (RSV), has developed an intranasal live-attenuated chimeric vaccine. Chimeric vaccines integrate genomic content from multiple viruses to create a more stable LAV [[50](#ref-14GSJSuHC)]. Enrollment for phase I human trials began in March 2021 and recruitment is ongoing [[47](#ref-iCUWeMfX),[293](#ref-8ZMg94iW)].

Finally, Bacillus Calmette-Guerin (BCG) vaccines that use LAVs are being investigated for the prophylaxis of COVID-19. The purpose of the BCG vaccine is to prevent tuberculosis, but non-specific effects against other respiratory illnesses have suggested a possible benefit against COVID-19 [[51](#ref-1CJtdlM6d)]. Currently, investigations of BCG vaccines against COVID-19 are being sponsored by institutes in Australia in collaboration with the Bill and Melinda Gates Foundation [[294](#ref-9m3rP633)] and by Texas A&M University in collaboration with numerous other U.S. institutions [[295](#ref-xdqxBruc)].

All the same, results from LAV trials in humans are largely unavailable, and no LAV vaccines are being administered. Despite the long and trusted history of LAV development, this vaccine strategy has not been favored against COVID-19. Modern, modular technologies have shown greater expediency and safety compared to the time-consuming nature of developing LAVs for a novel virus.

## 1.2 Sinovac’s CoronaVac

Pre-clinical trials were performed using BALB/c mice and rhesus macaques [[67](#ref-14fILrRWg)]. The SARS-CoV-2 strains used in this trial isolated from 11 hospitalized patients (5 from China, 3 from Italy, 1 from the UK, 1 from Spain, 1 from Switzerland). A phylogenetic analysis demonstrated that the strains were representative of the variants circulating at the time. One of the strains from China, CN2, was used as the inactivated and purified virus while the other 10 strains were used to challenge. The CN2 was grown in Vero cells. An ELISA assay was used to assess the immunogenicity of the vaccine. 10 mice were injected with the vaccine on day 0 and day 7 with varying doses (0, 1.5, 3 or 6 μg), and 10 mice were treated with physiological saline as the control. IgG developed in the serum of all vaccinated mice. Using the same setup, immunogenicity was also assessed in macaques. Four macaques were assigned to each of four groups: treatment with 3 μg at day 0, 7 and 14, treatment with a high dose of 6 μg at day 0, 7 and 14, administration of a placebo vaccine, and administration of only the adjuvant. All vaccinated macaques induced IgGs and neutralizing antibodies. After challenge with SARS-CoV-2 strain CN1, vaccinated macaques were protected compared to control macaques (placebo or adjuvant only) based on histology and viral loads collected from different regions of the lung.

Phase I/II clinical trials were conducted in adults 18-59 years old [[68](#ref-N1txjPtt)] and adults over 60 years old [[66](#ref-Ozya5HP5)] in China. In the case of adults 18-59 years old, a single center, randomized, double-blind, placebo-controlled phase I/II trial was conducted in April 2020. Patients in this study were recruited from the community in Suining County of Jiangsu province, China. For the phase I trial, 144 (of 185 screened) participants were enrolled, with 72 enrolled in the 14-day interval cohort (i.e., treated on day 0 and day 14) and 72 in the 28-day interval cohort. This group of 72 participants was split into 2 blocks for a low-dose (3 μg) and high-dose (6 μg) vaccine. Within each block, participants were randomly assigned vaccination with CoronaVac or placebo (aluminum diluent without the virus) at a 2:1 ratio. Both the vaccine and placebo were prepared in a Good Manufacturing Practice-accredited facility of Sinovac Life Sciences (Beijing, China).

The phase II trial followed the same organization of participants, this time using 300 enrolled participants in the 14-day and another 300 enrolled in the 28-day groups. One change of note was that the vaccine was produced using a highly automated bioreactor (ReadyToProcess WAVE 25, GE, Umeå, Sweden) to increase vaccine production capacity. This change resulted in a higher intact spike protein content. The authors of this study were not aware of this antigen-level difference between the vaccine batches for the phase I/II when the ethical approval for the trials occurred.

To assess adverse responses, participants were asked to record any events up to 7 days post-treatment. The reported adverse events were graded according to the China National Medical Products Administration guidelines. In the phase I trial, the overall incidence of adverse reactions was 29-38% of patients in the 0 to 14 day group and 13-17% in the 0 to 28 day vaccination group. The most common symptom was pain at the injection site, which was reported by 17-21% of patients in the 0 to 14 day cohort and 13% in the 0 to 28 day cohort. Most adverse reactions were mild (grade 1) where patients recovered within 48 hours. A single case of acute hypersensitivity with manifestation of urticaria 48 hours following the first dose of study drug was reported in the 6 μg group. Most of the adverse reactions reported were characterized as mild and resolved within 48 hours, with a single participant experiencing a serious adverse event that could have been related to vaccination (acute hypersensitivity with manifestation of urticaria 48 hours after their first dose in the 6-μg condition). Both the 14-day and 28-day cohorts had a strong neutralizing Ab response. The neutralizing Ab response was measured using a micro cytopathogenic effect assay, which assesses the minimum dilution of neutralizing Ab to be 50% protective against structural changes in host cells in response to viral infection [[296](#ref-1GUVvcQjL)]. Additionally IgG antibody titers against the receptor binding domain were also measured using ELISA.

Another phase I/II study was performed with older patients (older than 60 years) [[66](#ref-Ozya5HP5)]. The study conducted a single-center, randomized, double-blind, placebo-controlled trial. The phase I trial looked at dose escalation using 3 dosages: 1.5, 3 and 6 μg. The mean age of participants was 65.8 years (std = 4.8). Of 95 screened participants, 72 were enrolled. These 72 participants were split into low (3 μg) and high (6 μg) dose groups. Within each group, 24 participants received the treatment and 12 the placebo. A neutralizing antibody response against live SARS-CoV-2 was detected compared to baseline using the same micro cytopathogenic effect assay. This response was similar across the two dose concentrations. Additionally, they did not observe a difference in response between age groups (60–64 years, 65–69 years, and ≥70 years).

In phase II the mean age was 66.6 years (standard deviation = 4.7). 499 participants were screened and 350 were enrolled. 300 were evenly split into 1.5, 3 and 6 μg dose groups, and the remaining 50 were assigned to the placebo group. Again, they found a neutralizing antibody response in phase II. There wasn’t a significant different between the response to 3 μg versus 6 μg, but the response was higher than that to 1.5 μg.

Participants were required to record adverse reaction events within the first 7 days after each dose. The safety results were combined across phage I and II. All adverse reactions were either mild (grade 1) or moderate (grade 2) in severity. The most common symptom was pain at the injection site (9%) and fever (3%). 2% (7 participants) reported severe adverse events (4 from the 1.5 μg group, 1 from the 3 μg group, 2 from the 6 μg group), though these were found to be unrelated to the vaccine.

Overall, the results from the pre-clinical and phase I/II clinical trials are promising. It was also very hopeful to see that the immune response was consistent in older adults (> 60 years). Currently, phase III trials are being conducted in Brazil [[297](#ref-KewHbkLZ)]. This is a randomized, multicenter, endpoint driven, double-blind, placebo-controlled clinical trial. They are expecting 13,060 participants with 11,800 ages 18 to 59 years and 1,260 age 60+. Participants will be health care professionals. As of September 2021, CoronaVac trials are now also being held in the Philippines and Hong Kong, bringing the total number of registered phase III trials investigating the safety and efficacy of CoronaVac to 9, with emergency use approval in 40 countries [[298](#ref-19z4gdhDS)].

## 1.3 COVAXIN

In India, the COVAXIN® vaccine received emergency authorization on January 3rd, 2021, despite the lack of phase III data until March 3rd, which was communicated via press release [[299](#ref-Ks3L7qHG)]. Following a press release of the phase III data indicating 80.6% efficacy in 25,800 participants [[299](#ref-Ks3L7qHG),[300](#ref-DaDKZXdu)], Zimbabwe authorized the use of COVAXIN® [[301](#ref-13yEnvOyP)]. This was followed by a detailed preprint of the double-blind, randomized, controlled phase III trial that was made available in July 2021, with a final enrollment of 25,798 people (~1:1 vaccine:placebo) [[86](#ref-n7BupOQ6)]. The vaccine was reported as well tolerated, with an overall vaccine efficacy of 77.8% for the prevention of COVID-19. Efficacy against severe disease and asymptomatic infection was reported as 93.4% and 63.6% respectively. Indeed, another preprint determined that sera from individuals immunized with COVAXIN® had effective neutralizing antibodies against the delta variant and the so-called delta plus variant (AY.1) [[92](#ref-lr7INjf6)]. It is not yet clear what level of protection COVAXIN® offers beyond 6 to 8 months post the second vaccine; consequently, the potential requirement of a booster immunization is being explored [[99](#ref-s1TGwKbT)]. Furthermore, Bharat Biotech is considering other vaccine regimens such as providing one initial immunization with COVAXIN® followed by two immunizations with its intranasal vaccine (BBV154) [[302](#ref-UU0pj3ii)]. U.S.-based Ocugen Inc., a co-development partner of Bharat Biotech, is leading the application for an Emergency Use Authorization (EUA) for COVAXIN® intended for the U.S. market. As of September 2021 COVAXIN® has been approved for emergency use in Guyana, India, Iran, Zimbabwe, and Nepal, Mauritius, Mexico, Nepal, Paraguay, and the Philippines [[80](#ref-19tYVbg8H)]. It has been reported that Bharat Biotech will soon release its phase II and III pediatric trial results [[303](#ref-3Q7kvwO3)]. However, the WHO approval of the COVAXIN® has been delayed [[304](#ref-AeulXXFm)].

## 1.4 RNA Vaccines

RNA vaccines are nucleic-acid based modalities that code for viral antigens against which the human body elicits a humoral and cellular immune response. The mRNA technology is transcribed *in vitro* and delivered to cells via lipid nanoparticles (LNP) [[221](#ref-HCImhzy8)]. They are recognized by ribosomes *in vivo* and then translated and modified into functional proteins [[39](#ref-K0Ltu31S)]. The resulting intracellular viral proteins are displayed on surface MHC proteins, provoking a strong CD8+ T cell response as well as a CD4+ T cell and B cell-associated antibody responses [[39](#ref-K0Ltu31S)]. Naturally, mRNA is not very stable and can degrade quickly in the extracellular environment or the cytoplasm. The LNP covering protects the mRNA from enzymatic degradation outside of the cell [[222](#ref-zNKWlCwE)]. Codon optimization to prevent secondary structure formation and modifications of the poly-A tail as well as the 5’ untranslated region to promote ribosomal complex binding can increase mRNA expression in cells. Furthermore, purifying out double-stranded RNA and immature RNA with FPLC (fast performance liquid chromatography) and HPLC (high performance liquid chromatography) technology will improve translation of the mRNA in the cell [[39](#ref-K0Ltu31S),[223](#ref-pRoqjur8)]. Vaccines based on mRNA delivery confer many advantages over traditional viral vectored vaccines and DNA vaccines. In comparison to live attenuated viruses, mRNA vaccines are non-infectious and can be synthetically produced in an egg-free, cell-free environment, thereby reducing the risk of a detrimental immune response in the host [[226](#ref-wYZ6qJMu)]. Unlike DNA vaccines, mRNA technologies are naturally degradable and non-integrating, and they do not need to cross the nuclear membrane in addition to the plasma membrane for their effects to be seen [[39](#ref-K0Ltu31S)]. Furthermore, mRNA vaccines are easily, affordably, and rapidly scalable.

Although mRNA vaccines have been developed for therapeutic and prophylactic purposes, none have previously been licensed or commercialized. Nevertheless, they have shown promise in animal models and preliminary clinical trials for several indications, including rabies, coronavirus, influenza, and cytomegalovirus [[227](#ref-3EUiWZdN)]. Preclinical data previously identified effective antibody generation against full-length FPLC-purified influenza hemagglutinin stalk-encoding mRNA in mice, rabbits, and ferrets [[228](#ref-6wZy2mn8)]. Similar immunological responses for mRNA vaccines were observed in humans in Phase I and II clinical trials operated by the pharmaceutical-development companies Curevac and Moderna for rabies, flu, and zika [[223](#ref-pRoqjur8)]. Positively charged bilayer LNPs carrying the mRNA attract negatively charged cell membranes, endocytose into the cytoplasm [[222](#ref-zNKWlCwE)], and facilitate endosomal escape. LNPs can be coated with modalities recognized and engulfed by specific cell types, and LNPs that are 150 nm or less effectively enter into lymphatic vessels [[222](#ref-zNKWlCwE),[229](#ref-Djz8x39x)]. Therefore, this technology holds great potential for targeted delivery of modified mRNA.

There are three types of RNA vaccines: non-replicating, *in vivo* self-replicating, and *in vitro* dendritic cell non-replicating [[224](#ref-1EM5nGaYd)]. Non-replicating mRNA vaccines consist of a simple open reading frame (ORF) for the viral antigen flanked by the 5’ UTR and 3’ poly-A tail. *In vivo* self-replicating vaccines encode a modified viral genome derived from single-stranded, positive sense RNA alphaviruses [[39](#ref-K0Ltu31S),[223](#ref-pRoqjur8)]. The RNA genome encodes the viral antigen along with proteins of the genome replication machinery, including an RNA polymerase. Structural proteins required for viral assembly are not included in the engineered genome [[39](#ref-K0Ltu31S)]. Self-replicating vaccines produce more viral antigens over a longer period of time, thereby evoking a more robust immune response [[224](#ref-1EM5nGaYd)]. Finally, *in vitro* dendritic cell non-replicating RNA vaccines limit transfection to dendritic cells. Dendritic cells are potent antigen-presenting immune cells that easily take up mRNA and present fragments of the translated peptide on their MHC proteins, which can then interact with T cell receptors. Ultimately, primed T follicular helper cells can stimulate germinal center B cells that also present the viral antigen to produce antibodies against the virus [[225](#ref-3LMMW7F0)]. These cells are isolated from the patient, grown and transfected *ex vivo*, and reintroduced to the patient [[220](#ref-ENBWnhAh)].

Given the potential for this technology to be quickly adapted for a new pathogen, it has held significant interest for the treatment of COVID-19. In the vaccines developed under this approach, the spike protein, which is immunogenic [[231](#ref-5x25saIz)], can be furnished to the immune system in order to train its response. The vaccine candidates developed against SARS-CoV-2 using mRNA vectors utilize similar principles and technologies, although there are slight differences in implementation among candidates such as the formulation of the platform and the specific components of the spike protein encapsulated (e.g., the full Spike protein vs. the RBD alone) [[305](#ref-suRY1e0N)]. The results of the interim analyses of two mRNA vaccine candidates became available at the end of 2020 and provided strong support for this emerging approach to vaccination. Below we describe the results available as of February 2021 for two such candidates, mRNA-1273 produced by ModernaTX and BNT162b2 produced by Pfizer, Inc. and BioNTech.

### 1.4.1 ModernaTX mRNA Vaccine

ModernaTX’s mRNA-1273 vaccine was the first COVID-19 vaccine to enter a phase I clinical trial in the United States. In this trial, Moderna spearheaded an investigation on the immunogenicity and reactogenicity of mRNA-1273, a conventional lipid nanoparticle encapsulated RNA encoding a full-length prefusion stabilized S protein for SARS-CoV-2 [[234](#ref-Biu1CQeQ)]. An initial report described the results of enrolling forty-five participants who were administered intramuscular injections of mRNA-1273 in their deltoid muscle on day 1 and day 29, with the goal of following patients for the next twelve months [[15](#ref-wiGjCZC8)]. Healthy males and non-pregnant females aged 18-55 years were recruited for this study and divided into three groups receiving 25, 100, or 250 micrograms (μg) of mRNA-1273. IgG ELISA assays on patient serology samples were used to examine the immunogenicity of the vaccine [[234](#ref-Biu1CQeQ)]. Binding antibodies were observed at two weeks after the first dose at all concentrations. At the time point one week after the second dose was administered on day 29, the pseudotyped lentivirus reporter single-round-of-infection neutralization assay (PsVNA), which was used to assess neutralizing activity, reached a median level similar to the median observed in convalescent plasma samples. Participants reported mild and moderate systemic adverse events after the day 1 injection, and one severe local event was observed in each of the two highest dose levels. The second injection led to severe systemic adverse events for three of the participants at the highest dose levels, with one participant in the group being evaluated at an urgent care center on the day after the second dose. The reported localized adverse events from the second dose were similar to those from the first.

Several months later, a press release from ModernaTX described the results of the first interim analysis of the vaccine [[306](#ref-IMmoqofb)]. On November 16, 2020, a report was released describing the initial results from Phase III testing, corresponding to the first 95 cases of COVID-19 in the 30,000 enrolled participants [[306](#ref-IMmoqofb)], with additional data released to the FDA on December 17, 2020 [[307](#ref-QEdBZMLe)]. These results were subsequently published in a peer-reviewed journal (*The New England Journal of Medicine*) on December 30, 2020 [[236](#ref-ZYxoabEm)]. The first group of 30,420 study participants were randomized to receive the vaccine or a placebo at a ratio of 1:1 [[236](#ref-ZYxoabEm)]. Administration occurred at 99 sites within the United States in two sessions, spaced 28 days apart [[236](#ref-ZYxoabEm),[308](#ref-16kGLLlT8)]. Patients reporting COVID-19 symptoms upon follow-up were tested for SARS-CoV-2 using a nasopharyngeal swab that was evaluated with RT-PCR [[308](#ref-16kGLLlT8)]. The initial preliminary analysis reported the results of the cases observed up until a cut-off date of November 11, 2020. Of these first 95 cases reported, 90 occurred in participants receiving the placebo compared to 5 cases in the group receiving the vaccine [[306](#ref-IMmoqofb)]. These results suggested the vaccine is 94.5% effective in preventing COVID-19. Additionally, eleven severe cases of COVID-19 were observed, and all eleven occurred in participants receiving the placebo. The publication reported the results through an extended cut-off date of November 21, 2020, corresponding to 196 cases [[236](#ref-ZYxoabEm)]. Of these, 11 occurred in the vaccine group and 185 in the placebo group, corresponding to an efficacy of 94.1%. Once again, all of the severe cases of COVID-19 observed (n=30) occurred in the placebo group, including one death. Thus, as more cases are reported, the efficacy of the vaccine has remained above 90%, and no cases of severe COVID-19 have yet been reported in participants receiving the vaccine.

These findings suggest the possibility that the vaccine might bolster immune defenses even for subjects who do still develop a SARS-CoV-2 infection. The study was designed with an explicit goal of including individuals at high risk for COVID-19, including older adults, people with underlying health conditions, and people of color [[309](#ref-vkczroFC)]. The Phase III trial population was comprised by approximately 25.3% adults over age 65 in the initial report and 24.8% in the publication [[308](#ref-16kGLLlT8)]. Among the cases reported by both interim analyses, 16-17% occurred in older adults [[236](#ref-ZYxoabEm),[306](#ref-IMmoqofb)].. Additionally, approximately 10% of participants identified a Black or African-American background and 20% identified Hispanic or Latino ethnicity [[236](#ref-ZYxoabEm),[308](#ref-16kGLLlT8)]. Among the first 95 cases, 12.6% occurred in participants identifying a Hispanic or Latino background and 4% in participants reporting a Black or African-American background [[306](#ref-IMmoqofb)]; in the publication, they indicated only that 41 of the cases reported in the placebo group and 1 case in the treatment group occurred in “communities of color”, corresponding to 21.4% of all cases [[236](#ref-ZYxoabEm)]. While the sample size in both analyses is small relative to the study population of over 30,000, these results suggest that the vaccine is likely to be effective in people from a variety of backgrounds. By all indications, this vaccine is likely to be highly useful in mitigating the damage of SARS-CoV-2.

In-depth safety data was released by ModernaTX as part of their application for an EUA from the FDA and summarized in the associated publication [[236](#ref-ZYxoabEm),[308](#ref-16kGLLlT8)]. Because the detail provided in the report is greater than that provided in the publication, here we emphasize the results observed at the time of the first analysis. Overall, a large percentage of participants reported adverse effects when solicited, and these reports were higher in the vaccine group than in the placebo group (94.5% versus 59.5%, respectively, at the time of the initial analysis) [[308](#ref-16kGLLlT8)]. Some of these events met the criteria for grade 3 (local or systemic) or grade 4 (systemic only) toxicity [[308](#ref-16kGLLlT8)], but most were grade 1 or grade 2 and lasted 2-3 days [[236](#ref-ZYxoabEm)]. The most common local adverse reaction was pain at the injection site, reported by 83.7% of participants receiving the first dose of the vaccine and 88.4% upon receiving the second dose, compared to 19.8% and 19.8% and 17.0%, respectively, of patients in the placebo condition [[308](#ref-16kGLLlT8)]. Fewer than 5% of vaccine recipients reported grade 3 pain at either administration. Other frequent local reactions included erythema, swelling, and lymphadenopathy [[308](#ref-16kGLLlT8)]. For systemic adverse reactions, fatigue was the most common [[308](#ref-16kGLLlT8)]. Among participants receiving either dose of the vaccine, 68.5% reported fatigue compared to 36.1% participants receiving the placebo [[308](#ref-16kGLLlT8)]. The level of fatigue experienced was usually fairly mild, with only 9.6% and 1.3% of participants in the vaccine and placebo conditions, respectively, reporting grade 3 fatigue [[308](#ref-16kGLLlT8)], which corresponds to significant interference with daily activity [[310](#ref-oJWLuU0h)]. Based on the results of the report, an EUA was issued on December 18, 2020 to allow distribution of this vaccine in the United States [[238](#ref-13Ou1UUAd)], and it was shortly followed by an Interim Order authorizing distribution of the vaccine in Canada [[311](#ref-HwoGQ6DD)] and a conditional marketing authorization by the European Medicines Agency to facilitate distribution in the European Union [[312](#ref-4hVgIXyi)].

### 1.4.2 Pfizer/BioNTech BNT162b2

ModernaTX was, in fact, the second company to release news of a successful interim analysis of an mRNA vaccine and receive an EUA. The first report came from Pfizer and BioNTech’s mRNA vaccine BNT162b2 on November 9, 2020 [[313](#ref-16hlR7Xgi)], and a preliminary report was published in the *New England Journal of Medicine* one month later [[235](#ref-CWlYjjIV)]. The vaccine candidate is contains the full prefusion stabilized, membrane-anchored SARS-CoV-2 spike protein in a vaccine formulation based on modified mRNA (modRNA) technology [[232](#ref-1CsCQi9wT),[233](#ref-10VyxCgQU)]. This vaccine candidate should not be confused with a similar candidate from Pfizer/BioNTech, BNT162b1, that delivered only the RBD of the spike protein [[314](#ref-dlqAfQ7t),[315](#ref-T3BkYtz2)], which was not advanced to a stage III trial because of the improved reactogenicity/immunogenicity profile of BNT162b2 [[316](#ref-MD2K7MYB)].

During the Phase III trial of BNT162b2, 43,538 participants were enrolled 1:1 in the placebo and the vaccine candidate and received two 30-μg doses 21 days apart [[235](#ref-CWlYjjIV)]. Of these enrolled participants, 21,720 received BNT162b2 and 21,728 received a placebo [[235](#ref-CWlYjjIV)]. Recruitment occurred at 135 sites across six countries: Argentina, Brazil, Germany, South Africa, Turkey, and the United States. An initial press release described the first 94 cases, which were consistent with 90% efficacy of the vaccine at 7 days following the second dose [[313](#ref-16hlR7Xgi)]. The release of the full trial information covered a longer period and analyzed the first 170 cases occurring at least 7 days after the second dose, 8 of which occurred in patients who had received BNT162b2. The press release characterized the study population as diverse, reporting that 42% of the participants worldwide came from non-white backgrounds, including 10% Black and 26% Hispanic or Latino [[317](#ref-EMWkcH5x)]. Within the United States, 10% and 13% of participants, respectively, identified themselves as having Black or Hispanic/Latino backgrounds [[317](#ref-EMWkcH5x)]. Additionally, 41% of participants worldwide were 56 years of age or older [[317](#ref-EMWkcH5x)], and they reported that the efficacy of the vaccine in adults over 65 was 94% [[318](#ref-Ufs4s7hG)]. The primary efficacy analysis of the Phase III study was concluded on November 18, 2020 [[318](#ref-Ufs4s7hG)], and the final results indicted 94.6% efficacy of the vaccine [[235](#ref-CWlYjjIV)].

The safety profile of the vaccine was also assessed [[235](#ref-CWlYjjIV)]. A subset of patients were followed for reactogenicity using electronic diaries, with the data collected from these 8,183 participants comprising the solicited safety events analyzed. Much like those who received the ModernaTX vaccine candidate, a large proportion of participants reported experiencing site injection pain within 7 days of vaccination. While percentages are broken down by age group in the publication, these proportions correspond to approximately 78% and 73% of all participants after the first and second doses, respectively, overall. Only a small percentage of these events (less than 1%) were rated as serious, with the rest being mild or moderate, and none reached grade 4. Some participants also reported redness or swelling, and the publication indicates that in most cases, such events resolved within 1 to 2 days. Participants also experienced systemic effects, including fever (in most cases lower than 38.9°C and more common after dose 2), fatigue (25-50% of participants depending on age group and dose), headache (25-50% of participants depending on age group and dose), chills, and muscle or joint pain; more rarely, patients could experience gastrointestinal effects such as vomiting or diarrhea. As with the local events, these events were almost always grade I or II. While some events were reported by the placebo groups, these events were much rarer than in the treatment group even though compliance was similar. Based on the efficacy and safety information released, the vaccine was approved in early December by the United Kingdom’s Medicines and Healthcare Products Regulatory Agency with administration outside of a clinical trial beginning on December 8, 2020 [[319](#ref-31rsgfCB),[320](#ref-fhw7l8VO)]. As of December 11, 2020, the United States FDA approved this vaccine under an emergency use authorization [[237](#ref-cAaN4Te0)].

## 1.5 Viral Vector Vaccines

### 1.5.1 ChAdOx1 nCoV-19 (AstraZeneca)

As discussed above, prior analyses of viral vector vaccines against hCoV had indicated that this approach showed potential for inducing an immune response, but little information was available about the effect on real-world immunity. In the first phase of development, a candidate ChAdOx1 nCoV-19 was evaluated through the immune challenge of two animal models, mice and rhesus macaques [[198](#ref-1037p4Gvs)]. Animals in the treatment condition were observed to develop neutralizing antibodies specific to SARS-CoV-2 (both macaques and mice) and to show reduced clinical scores when exposed to SARS-CoV-2 (macaques) [[198](#ref-1037p4Gvs)]. Next, a phase I/II trial was undertaken using a single-blind, randomized controlled design [[199](#ref-2bBVSpM)]. ChAdOx1 nCoV-19 and a control, the meningococcal conjugate vaccine MenACWY, were administered intramuscularly to adults ages 18 to 55 at five sites within the United Kingdom (U.K.) at a 1:1 ratio (n=543 and n=534, respectively). All but ten participants received a single dose; this small group received a booster 28 days after their first dose of ChAdOx1 nCoV-19. Commonly reported local adverse reactions included mild-to-moderate pain and tenderness at the injection site over the course of seven days, while the most common systemic adverse reactions were fatigue and headache; some patients reported severe adverse systemic effects. The study also reported that many common reactions could be reduced through the administration of paracetamol (acetaminophen), and paracetamol was not found to reduce immunogenicity. Patients receiving the ChAdOx1 nCoV-19 vaccine developed antibodies to the SARS-CoV-2 spike protein that peaked by day 28, with these levels remaining stable until a second observation at day 56 except in the ten patients who received a booster dose at day 28, in whom they increased by day 56. Analysis of serum indicated that participants developed antibodies to both S and the RBD, and that 100% of them achieved neutralizing titers by day 28. By day 35, the neutralization titers of vaccinated patients was comparable to that observed with plasma from convalescents. This initial study therefore suggested that the vaccine was likely to confer protection against SARS-CoV-2, although analysis of its efficacy in preventing COVID-19 was not reported.

In December 2020, preliminary results of the phase III trial were released detailing randomized control trials conducted in the U.K., Brazil, and South Africa between April and November 2020 [[12](#ref-Vnbw9o3T)]. These trials again compared ChAdOx1 nCoV-19 to a control, but the design of each study varied. For example, in South Africa, the trial was double-blinded, whereas in the U.K. and Brazil it was single-blinded, and one of the two trials carried out in the U.K. examined two dosing regimens (low dose or standard dose, both followed by standard dose). Some of the trials used MenACWY as a control, while others used saline. Data was pooled across countries for analysis. The primary outcome assessed was symptomatic, laboratory-confirmed COVID-19. There were 131 cases observed among the 11,636 participants eligible for the primary efficacy analysis, corresponding to an overall efficacy of 70.4% (30 out of 5807 in the vaccine arm and 101 out of 5829 in the control arm); the 95.8% CI was reported as 54.8 to 80.6. However, a higher efficacy was reported in the subgroup of patients who received a low-dose followed by a standard dose (90.0%, 95% CI 67.4 to 97·0). A total of ten cases of severe COVID-19 resulting in hospitalization were observed among trial participants, and all of these occurred in patients in the control arm of the study. In line with the previously reported safety profiling for this vaccine, serious adverse events were reported to be comparable across the two arms of the study, with only three events identified as potentially associated with the vaccine itself. The U.K. Medicines and Healthcare Products Regulatory Agency (MHRA) approved ChAdOx1 nCoV-19 for emergency use on December 30, 2020 [[211](#ref-1A7PjhDDR)]. Additional data about the efficacy of this vaccine became available in a preprint released on March 2, 2021 [[321](#ref-eV6UplSu)]. This report provided data describing the efficacy of ChAdOx1 nCoV-19, along with Pfizer/BioNTech’s BNT162b2, in the U.K. between December 8, 2020 and February 19, 2021 and specifically sought to evaluate the efficacy of the vaccine in the presence of a potentially more contagious variant of concern, B.1.1.7. All participants in this study were age 70 or older and the efficacy was estimated to increase from 60% at 28 days after vaccination to 73% at 35 days after vaccination, although the standard error also increased over this time. Therefore, preliminary results suggest that in a number of samples, this vaccine confers a high level of protection against SARS-CoV-2.

### 1.5.2 Sputnik-V (Gam-COVID-Vac and Gam-COVID-Vac-Lyo)

The vaccine Gam-COVID-Vac, nicknamed Sputnik V in reference to the space race and “V for vaccine”, was developed by the Gamaleya National Center of Epidemiology and Microbiology in Moscow. Gamaleya is an organization with prior experience using the adenovirus platform for the development of vaccines for *Middle East respiratory syndrome-related coronavirus* and Ebola virus, although neither of the previous vaccines were internationally licensed [[194](#ref-UCI0TCHy)]. The development of Sputnik V was financed by the Russian Direct Investment Fund (RDIF) [[200](#ref-3KMxmQhV),[322](#ref-SxiGicKs)]. Sputnik V is a replication-deficient recombinant adenovirus (rAd) vaccine that combines two adenovirus vectors, rAd26-S and rAd5-S, that express the full-length SARS-CoV-2 spike glycoprotein. These vectors are intramuscularly administered individually using two separate vaccines in a prime-boost regimen. The rAd26-S is administered first, followed by rAd5-S 21 days later. Both vaccines deliver 1011 viral particles per dose. This approach is designed to overcome any potential pre-existing immunity to adenovirus in the population [[323](#ref-sRAZYY9C)], as some individuals may possess immunity to Ad5 [[324](#ref-8jwp261S)]. Sputnik V is the only recombinant adenovirus vaccine to utilize two vectors. Other vaccines, such as the Oxford-AstraZeneca vaccine, utilize the chimpanzee adenovirus vector (ChAdOx1 nCoV-19) for both doses [[325](#ref-LZ8AtMnD)]. The Sputnik V vaccines are available in both a lyophilized (Gam-COVID-Vac-Lyo) and frozen form (Gam-COVID-Vac), which are stored at 2-8°C and -18°C respectively [[268](#ref-PNZEiId1)]. The lyophilized vaccine is convenient for distribution and storage, particularly to remote or disadvantaged areas [[326](#ref-3KBugyZN)].

In the race to develop vaccines against SARS-CoV-2, President Vladimir Putin of Russia announced the approval of the Sputnik V vaccines on August 11th, 2020 in the absence of clinical evidence [[200](#ref-3KMxmQhV)]. Consequently, many international scientific agencies and public health bodies expressed concern that due diligence to the clinical trial process was subverted for the sake of expediency, leading many to question the safety and efficacy of Sputnik V [[200](#ref-3KMxmQhV),[327](#ref-15DiM98Ae),[328](#ref-x4aIj5Fr)]. Despite regulatory, safety, and efficacy concerns, pre-orders for 1 billion doses of the Sputnik V were reported within days of the vaccine’s approval in Russia [[200](#ref-3KMxmQhV)]. Almost a month later, the phase I/II trial data was published [[268](#ref-PNZEiId1)].

In the phase I/II trial study conducted between late June and early August 2020, 76 participants (18-60 years old) were split into two groups of 38 participants, which were non-randomized in two hospitals in Russia. In phase I, 9 patients received rAd26 and 9 patients received rAd5-S to assess safety over 28 days. In phase II, at least 5 days after the completion of phase I, 20 patients received a prime-boost vaccination of rAd26-S on day 0 and rAd5-S on day 2, which was administered intramuscularly. The phase I/II trial reported that both vaccines were deemed safe and well tolerated. The most common adverse events reported were mild, such as pain at the injection site (58%), hypothermia (50%), headaches (42%), fatigue (28%), and joint and muscle pain (24%). Seroconversion was observed in all participants three weeks post the second vaccination (day 42), and all participants produced antibodies to the SARS-CoV-2 glycoprotein. RBD-specific IgG levels were high in both the frozen and lyophilized versions of the vaccine (14,703 and 11,143 respectively), indicating a sufficient immune response to both. Three weeks post the second vaccination, the virus-neutralizing geometric mean antibody titers were 49.25 and 45.95 from the frozen and lyophilized vaccines, respectively. At 28 days, median cell proliferation of 1.3% CD4+ and 1.1% CD8+ were reported for the lyophilized vaccine and 2.5% CD4+ and 1.3% CD8+ for the vaccine stored frozen. These results indicated that both forms of Sputnik V appeared to be safe and induce a humoral and cellular response in human subjects [[268](#ref-PNZEiId1)], which may be robust enough to persist and not wane rapidly [[323](#ref-sRAZYY9C)].

A press release on November 11th, 2020 indicated positive results from an interim analysis of the phase III Sputnik V trials, which reported 92% efficacy in 16,000 volunteers [[329](#ref-JSzDvnk6)]. However, this release came only two days after both Pfizer and BioNTech reported that their vaccines had an efficacy over 90%, which led to significant skepticism of the Russian findings for a myriad of reasons including the lack of a published protocol and the “reckless” approval of the vaccine in Russia months prior to the publication of the interim results of the phase III trial [[329](#ref-JSzDvnk6),[330](#ref-Yzz3rwqk)]. In February 2021, the interim results of the phase III randomized, double-blind, placebo-controlled trial were eventually published in *The Lancet* [[208](#ref-gLAIyAHm)]. The participants were randomly assigned to receive either a 0.5 mL/dose of vaccine or placebo, which was comprised of the vaccine buffer composition, that was delivered intramuscularly using the same prime-boost regimen as in the phase I/II trials. From September 7th to Nov 24th, 19,866 participants completed the trial. Of the 14,964 participants who received the vaccine, 16 (0.1%) were confirmed to have COVID-19, whereas 62 of the 4,902 participants (1.3%) in the placebo group were confirmed to have COVID-19. Of these participants, no moderate or severe cases of COVID-19 were reported in the vaccine group, juxtaposed with 20 in the placebo group. However, only symptomatic individuals were confirmed for SARS-CoV-2 infection in this trial. Therefore, asymptomatic infections were not detected, thus potentially inflating the efficacy estimate. Overall, a vaccine efficacy of 91.6% (95% CI 85.6-95.2) was reported, where an efficacy of 91.8% was reported for those over 60 years old and 92.7% for those who were 51-60 years old. Indeed, 14 days after the first dose, 87.6% efficacy was achieved and the immunity required to prevent disease occurred within 18 days of vaccination. Based on these results, scientists are investigating the potential for a single dose regimen of the rAd26-S sputnik V vaccine [[331](#ref-wCTVieA3)]. By the end of the trial, 7,485 participants reported adverse events, of which 94% were grade I. Of the 68 participants who experienced serious adverse events during the trial, 45 from the vaccine group and 23 from the placebo groups, none were reported to be associated with the vaccination. Likewise, 4 deaths occurred during the trial period that were not related to the vaccine [[208](#ref-gLAIyAHm)]. The interim findings of the phase III trial indicate that the Sputnik V vaccine regimen appears to be safe with 91.6% efficacy. Gamaleya had intended to reach a total of 40,000 participants for the completion of their phase III trial. However, the trial has stopped enrolling participants and the numbers have been cut to 31,000 as many individuals in the placebo group dropped out of the study to obtain the vaccine [[332](#ref-15qYogj0H)]. Indeed, other trials involving Sputnik V are currently underway in Belarus, India, the United Arab Emirates, and Venezuela [[333](#ref-vrzaW9Gb)].

Preliminary results of a trial of Argentinian healthcare workers in Buenos Aires who were vaccinated with the Sputnik V rAd26-R vector-based vaccine seems to support the short term safety of the first vaccination [[334](#ref-uOMlbWFc)]. Of the 707 vaccinated healthcare workers, 71.3% of the 96.6% of respondents reported at least one adverse event attributed to the vaccine. Of these individuals, 68% experienced joint and muscle pain, 54% had injection site pain, 11% reported redness and swelling, 40% had a fever, and 5% reported diarrhea. Only 5% of the vaccinated participants experienced serious adverse events that required medical attention, of which one was monitored as an inpatient.

Additionally, an Independent assessment of Sputnik V in a phase II clinical trial in India found the vaccine to be effective, but the data is not yet publicly available [[335](#ref-jv875POj)]. On December 21st, 2020, Gamaleya, AstraZeneca, R-Pharm, and the Russian Direct Investment Fund agreed to assess the safety and immunogenicity of the combined use of components of the AstraZeneca and University of Oxford AZD1222 (ChAdOx1) vaccine and the rAd26-S component of the Sputnik V vaccine in clinical trials [[336](#ref-QzHvKB8C)]. This agreement hopes to establish scientific and business relations between the entities with an aim to co-develop a vaccine providing long-term immunization. The trial, which will begin enrollment soon, will include 100 participants in a phase II open-label study and is hoped to be complete within 6 months. Participants will first receive an intramuscular dose of AZD1222 on day 1, followed by a dose of rAd26 on day 29. Participants will be monitored from day 1 for 180 days in total. The primary outcomes measured will include incidence of serious adverse events post first dose until the end of the study. Secondary outcome measures will include incidence of local and systemic adverse events 7 days post each dose, a time course of antibody responses for the Spike protein and the presence of anti-SARS-CoV-2 neutralizing antibodies [[337](#ref-1G2ROkAsZ)].

Overall, there is hesitancy surrounding the management of the Sputnik V vaccine approval process and concerns over whether the efficacy data may be inflated due to a lack of asymptomatic testing within the trial. However, the interim results of the phase III study were promising and further trials are underway, which will likely shed light on the overall efficacy and safety of the Sputnik V vaccine regimen. There may be some advantage to the Sputnik V approach including the favorable storage conditions afforded by choice between a frozen and lyophilized vaccine. Furthermore, the producers of Gam-COVID-Vac state that they can produce the vaccine at a cost of less than $10 per dose or less than $20 per patient [[338](#ref-AfkC38Sh)].

### 1.5.3 Janssen’s JNJ-78436735

The Johnson & Johnson (J&J) vaccine developed by Janssen Pharmaceuticals, Inc., a subsidiary of J&J, was conducted in collaboration with and funded by “Operation Warp Speed” [[201](#ref-D3Px25HN),[202](#ref-57BTbcko)]. The vaccine candidate JNJ-78436735, formerly known as Ad26.COV2-S, is a monovalent vaccine that is composed of a replication-deficient adenovirus serotype 26 (Ad26) vector expressing the stabilized pre-fusion S protein of SARS-CoV-2 [[28](#ref-10UC562ga),[203](#ref-pWf2T8J8)]. The vaccine was developed using Janssen’s AdVac® and PER.C6 platforms that were previously utilized to develop the European Commission-approved Ebola vaccine (Ad26 ZEBOV and MVN-BN-Filo) and their Zika, respiratory syncytial (RSV), and HIV investigational vaccine candidates [[339](#ref-10uLoe1rR)].

The development of a single-dose vaccine was desirable by J&J from the outset, with global deployment being a key priority [[204](#ref-gOOBv1MD)]. Using their AdVac® technology, the vaccine can remain stable for up to two years between -15℃ and -25℃ and at least three months at 2-8℃ [[339](#ref-10uLoe1rR)]. This allows the vaccine to be distributed easily without the requirement for very low temperature storage, unlike many of the other COVID-19 vaccine candidates. J&J screened numerous potential vaccine candidates *in vitro* and in animal models using varying different designs of the S protein, heterologous signal peptides, and prefusion-stabilizing substitutions [[28](#ref-10UC562ga)]. A select few candidates were further investigated as a single dose regimen in Syrian golden hamsters, a single dose regimen in rhesus macaques, and a single- and two-dose regimen in both adult and aged rhesus macaques [[28](#ref-10UC562ga),[204](#ref-gOOBv1MD),[205](#ref-HmMIiIv2),[206](#ref-EpOXYGt4)]. From these studies, the JNJ-78436735 candidate was selected for its favorable immunogenicity profile and ease of manufacturability [[28](#ref-10UC562ga),[204](#ref-gOOBv1MD),[205](#ref-HmMIiIv2),[206](#ref-EpOXYGt4)]. A SARS-CoV-2 challenge study in rhesus macaques showed that vaccine doses as low as 2 x 109 viral particles/mL was sufficient to induce strong protection in bronchoalveolar lavage but that doses higher than 1.125 x 1010 were required to close achieve close to complete protection in nasal swabs [[340](#ref-lVoienSE)]. Indeed, six months post-immunization, levels of S-binding and neutralizing antibodies in rhesus macaques indicated that the JNJ-78436735 vaccine conferred durable protection against SARS-CoV-2 [[207](#ref-HGVDPMLm)].

Following selection of the JNJ-78436735 vaccine, J&J began phase I/IIa trials. The interim phase I/IIa data was placed on the *medRxiv* preprint server on September 25th, 2020 [[341](#ref-14g52GtO3)] and was later published in the *New England Journal of Medicine* on January 13th, 2021 [[203](#ref-pWf2T8J8)]. The phase I/IIa multi-center, randomized, placebo-controlled trial enrolled 402 healthy participants between 18-55 years old and a further 403 healthy older participants ≥ 65 years old [[203](#ref-pWf2T8J8)]. Patients were administered either a placebo, a low dose (5 x 1010 viral particles per mL), or a high dose (1 X 1011 viral particles per mL) intramuscularly as part of either a single- or two-dose regimen. All patients received injections 56 days apart, but participants in the single-dose condition received the placebo at the second appointment. Those who received only one dose of either vaccine received a placebo dose at their second vaccination visit. A comparison of the single versus double dose regimen has yet to be published. The primary endpoints of both the trial were safety and reactogenicity of each dose. Fatigue, headache, myalgia, and pain at the injection site were the most frequent solicited adverse events reported by participants. Although less common, particularly for those in the elderly cohort and those on the low dose regimen, the most frequent systemic adverse effect was fever. Overall, immunization was well tolerated, particularly at the lower dose concentration. In terms of reactogenicity, over 90% of those who received either the low or high dose demonstrated seroconversion in a neutralization assay using wild-type SARS-CoV-2, 29 days after immunization [[203](#ref-pWf2T8J8)]. Neutralizing geometric mean ratio of antibody titers (GMT) between 224-354 were detected regardless of age. By day 57, 100% of the 18-55 year old participants had neutralizing GMT (288-488), which remained stable until day 71. In the ≥ 65 years old cohort, the incidence of seroconversion for the low- and high-dose was 96% and 88% respectively by day 29.

GMTs for the low and high doses were slightly lower for participants ≥ 65 years old (196 and 127 respectively), potentially indicating slightly lower immunogenicity. Seroconversion of the S antibodies was detected in 99% of individuals between 18-55 years old for the low and high doses (GMTs 528 and 695 respectively), with similar findings reported for the ≥ 65 years old. Indeed, both dose concentrations also induced robust Th1 cytokine-producing S-specific CD4+ T cells and CD8+ T cell responses in both age groups. The findings of the phase I/IIa study supported further investigation of a single immunization using the low dose vaccine. Therefore, 25 patients were enrolled for a second randomized double-blind, placebo-controlled phase 1 clinical trial currently being conducted in Boston, Massachusetts for 2 years [[342](#ref-1CBMCD5I2)]. Participants received either a single dose followed by a placebo, or a double dose of either a low dose (5 x 1010 viral particles/mL) or a high dose (1 x 1011 viral particles/mL) vaccine administered intramuscularly on day 1 or day 57. Placebo-only recipients received a placebo dose on day 1 and 57. Interim analyses conducted on day 71 indicated that binding and neutralizing antibodies developed 8 days after administration in 90% and 25% of vaccine recipients, respectively. Binding and neutralizing antibodies were detected in 100% of vaccine recipients by day 57 after a single dose immunization. Spike-specific antibodies were highly prevalent (GMT 2432 to 5729) as were neutralizing antibodies (GMT 242 to 449) in the vaccinated groups. Indeed, CD4+ and CD8+ T-cell responses were also induced, which may provide additional protection, particularly if antibodies wane or poorly respond to infection [[343](#ref-1GRYnvF01)].

On September 23rd, 2020, J&J launched its phase III trial ENSEMBLE and released the study protocol to the public [[339](#ref-10uLoe1rR),[344](#ref-7n6WEkK8)]. The trial intended to enroll 60,000 volunteers to assess the safety and efficacy of the single vaccine dose versus placebo with primary endpoints of 14 and 28 days post-immunization [[339](#ref-10uLoe1rR)]. The trial was conducted in Argentina, Brazil, Chile, Colombia, Mexico, Peru, South Africa, and the U.S. The trial was paused briefly in October 2020 to investigate a “serious medical event”, but resumed shortly after [[345](#ref-5BTmfe4Y)]. An interim analysis was reported via press release on January 29th, 2021 [[209](#ref-iWMHpTBJ),[210](#ref-1FcpboRMm)]. The interim data included 43,783 participants who accrued 468 symptomatic cases of COVID-19. It was reported that the JNJ-78436735 vaccine was 66% effective across all regions studied for the prevention of moderate to severe COVID-19 28 days post-vaccination in those aged 18 years and older. Notably, JNJ-78436735 was 85% effective for the prevention of laboratory-confirmed severe COVID-19 and 100% protection against COVID-19-related hospitalization and death 28 days post-vaccination across all study sites. Efficacy of the vaccine against severe COVID-19 increased over time, and there were no cases of COVID-19 reported in immunized participants after day 49. The trial also determined that the vaccine candidate has a favorable safety profile as determined by an independent Data and Safety Monitoring Board. The vaccine was well tolerated, consistent with previous vaccines produced using the AdVac® platform. Fever occurred in 9% of vaccine recipients, with grade 3 fever occurring in only 0.2% of recipients. Serious adverse events were reportedly higher in the placebo group than the vaccine group, and no anaphylaxis was reported [[210](#ref-1FcpboRMm)].

At the time the phase III trial was being conducted, several concerning variants, including B.1.1.7 [[346](#ref-m9qtrWft)] and B.1.351 [[217](#ref-sqhvCTIL)], were spreading across the globe. In particular, B.1.351 was first identified in South Africa, which was one of the JNJ-78436735 vaccine trial sites. Therefore, the J&J investigators also analyzed the efficacy of the JNJ-78436735 vaccine associated with their various trial sites to determine any potential risk of reduced efficacy as a result of the novel variants. It was determined that JNJ-78436735 was 72% effective in the U.S., 66% effective in Latin America, and 57% effective in South Africa 28 days post-vaccination. These findings underpin the importance of monitoring for the emergence of novel SARS-CoV-2 variants and determining their effects on vaccine efficacy.

Looking forward, Janssen are also running a phase III randomized, double-blind, placebo-controlled clinical trial, Ensemble 2, which aims to assess the efficacy, safety, and immunogenicity of a two-dose regimen of JNJ-78436735 administered 57 days apart. This trial will enroll 30,000 participants ≥ 18 years old from Belgium, Colombia, France, Germany, Philippines, South Africa, Spain, U.K., and the U.S. [[347](#ref-sx7F1ktj)]. This trial will also include participants with and without comorbidities associated with an increased risk of COVID-19.

### 1.5.4 Overall Status of Viral-Vector Vaccines

The three viral-vector vaccines described above have demonstrated the potential for this technology to facilitate a quick response to an emerging pathogen. However, two of the three vaccines have faced a number of criticisms surrounding the implementation of their clinical trials. <–To Do: Suggestion to move some of the Sputnik controversy here, along with describing the issues with the AstraZeneca trial–>

Additionally, though the vaccines are built using similar principles, there are some differences that might influence their efficacy as SARS-CoV-2 evolves. <–To Do: suggestion to discuss prefusion conformation (J&J) vs not (the other two)–>

## 1.6 Sinovac’s CoronaVac

The CoronaVac vaccine is being developed by Sinovac, a Beijing-based biopharmaceutical company. The vaccine is using an inactivate whole virus with the addition of an aluminum adjuvant [[348](#ref-RGPoDfHS)]. The vaccine is currently in Phase III clinical trials.

Pre-clinical trials were performed using BALB/c mice and rhesus macaques [[67](#ref-14fILrRWg)]. The SARS-CoV-2 strains used in this trial isolated from 11 hospitalized patients (5 from China, 3 from Italy, 1 from the UK, 1 from Spain, 1 from Switzerland). A phylogenetic analysis demonstrated that the strains were representative of the current circulating variants. One of the strains, CN2, from China was used as the inactivated and purified virus while the other 10 strains were used to challenge. The CN2 was grown in Vero cells. An ELISA assay was used to assess the immunogenicity of the vaccine. 10 mice were injected with the vaccine on day 0 and day 7 with varying doses (0, 1.5, 3 or 6 μg), and 10 mice were treated with physiological saline as the control. IgG developed in the serum of all vaccinated mice. Using the same setup, immunogenicity was also assessed in macaques. Four macaques were assigned to each of four groups: treatment with 3 μg at day 0, 7 and 14, treatment with a high dose of 6 μg at day 0, 7 and 14, administration of a placebo vaccine, and administration of only the adjuvant. All vaccinated macaques induced IgGs and neutralizing antibodies. After challenge with SARS-CoV-2 strain CN1, vaccinated macaques were protected compared to control macaques (placebo or adjuvant only) based on histology and viral loads collected from different regions of the lung.

Phase I/II clinical trials were conducted in adults 18-59 years old [[68](#ref-N1txjPtt)] and adults over 60 years old [[66](#ref-Ozya5HP5)] in China. In the case of adults 18-59 years old, a single center, randomized, double-blind, placebo-controlled phase I/II trial was conducted in April 2020. Patients in this study were recruited from the community in Suining County of Jiangsu province, China. For the phase I trial, 144 (of 185 screened) participants were enrolled, with 72 enrolled in the 14-day interval cohort (i.e., treated on day 0 and day 14) and 72 in the 28-day interval cohort. This group of 72 participants was split into 2 blocks for a low-dose (3 μg) and high-dose (6 μg) vaccine. Within each block, participants were randomly assigned vaccination with CoronaVac or placebo (aluminum diluent without the virus) at a 2:1 ratio. Both the vaccine and placebo were prepared in a Good Manufacturing Practice-accredited facility of Sinovac Life Sciences (Beijing, China).

The phase II trial followed the same organization of participants, this time using 300 enrolled participants in the 14-day and another 300 enrolled in the 28-day groups. One change of note was that the vaccine was produced using a highly automated bioreactor (ReadyToProcess WAVE 25, GE, Umeå, Sweden) to increase vaccine production capacity. This change resulted in a higher intact spike protein content. The authors of this study were not aware of this antigen-level difference between the vaccine batches for the phase I/II when the ethical approval for the trials occurred.

To assess adverse responses, participants were asked to record any events up to 7 days post-treatment. The reported adverse events were graded according to the China National Medical Products Administration guidelines. In the phase I trial, the overall incidence of adverse reactions was 29-38% of patients in the 0 to 14 day group and 13-17% in the 0 to 28 day vaccination group. The most common symptom was pain at the injection site, which was reported by 17-21% of patients in the 0 to 14 day cohort and 13% in the 0 to 28 day cohort. Most adverse reactions were mild (grade 1) where patients recovered within 48 hours. A single case of acute hypersensitivity with manifestation of urticaria 48 hours following the first dose of study drug was reported in the 6 μg group Most adverse reactions were mild (grade 1) in severity and participants recovered within 48 hours. There was a single case, from the 6 μg group, of acute hypersensitivity with manifestation of urticaria 48 hours after the first dose. Both the 14-day and 28-day cohorts had a strong neutralizing Ab response. The neutralizing Ab response was measured using a micro cytopathogenic effect assay, which assesses the minimum dilution of neutralizing Ab to be 50% protective against structural changes in host cells in response to viral infection [[296](#ref-1GUVvcQjL)]. Additionally IgG antibody titers against the receptor binding domain were also measured using ELISA.

Another phase I/II study was performed with older patients (older than 60 years) [[66](#ref-Ozya5HP5)]. The study conducted a single-center, randomized, double-blind, placebo-controlled trial. The phase I trial looked at dose escalation using 3 dosages: 1.5, 3 and 6 μg. The mean age of participants was 65.8 years (std = 4.8). Of 95 screened participants, 72 were enrolled. These 72 participants were split into low (3 μg) and high (6 μg) dose groups. Within each group, 24 participants received the treatment and 12 the placebo. A neutralizing antibody response against live SARS-CoV-2 was detected compared to baseline using the same micro cytopathogenic effect assay. This response was similar across the two dose concentrations. Additionally, they did not observe a difference in response between age groups (60–64 years, 65–69 years, and ≥70 years).

In phase II the mean age was 66.6 years (standard deviation = 4.7). 499 participants were screened and 350 were enrolled. 300 were evenly split into 1.5, 3 and 6 μg dose groups, and the remaining 50 were assigned to the placebo group. Again, they found a neutralizing antibody response in phase II. There wasn’t a significant different between the response to 3 μg versus 6 μg, but the response was higher than that to 1.5 μg.

Participants were required to record adverse reaction events within the first 7 days after each dose. The safety results were combined across phage I and II. All adverse reactions were either mild (grade 1) or moderate (grade 2) in severity. The most common symptom was pain at the injection site (9%) and fever (3%). 2% (7 participants) reported severe adverse events (4 from the 1.5 μg group, 1 from the 3 μg group, 2 from the 6 μg group), though these were found to be unrelated to the vaccine.

Overall, the results from the pre-clinical and phase I/II clinical trials are promising. It was also very hopeful to see that the immune response was consistent in older adults (> 60 years). Currently, phase III trials are being conducted in Brazil [[297](#ref-KewHbkLZ)]. This is a randomized, multicenter, endpoint driven, double-blind, placebo-controlled clinical trial. They are expecting 13,060 participants with 11,800 ages 18 to 59 years and 1,260 age 60+. Participants will be health care professionals.

### 1.6.1 Sinopharm (2 candidates)

Sinopharm Wuhan Institute also developed their SARS-CoV-2 inactivated vaccine using the WIV04 strain isolated from a patient at the Jinyintan Hospital in Wuhan, China [[73](#ref-miMRIMwa)]. This vaccine was also passaged in Vero cells, inactivated using β-propiolactone, and was adjuvanted with aluminum hydroxide. This vaccine is administered intramuscularly using 5 μg of virus per dose. Preclinical data providing supporting evidence for the use of this vaccine is not available publicly. Despite the lack of publicly available preclinical results, Sinopharm Wuhan Institute initiated phase I/II trials, which reported on varying dosing and prime-boost regimens. Neutralizing antibodies were detected in all groups 14 days after the final dose in the phase I part of the trial [[75](#ref-T3MYavsH)]. Similar findings were reported in the Interim phase II data [[75](#ref-T3MYavsH)].

A combined phase I/II RCT of SinoPharm’s BBIBP-CorV followed [[81](#ref-fPGgVKYL)]. In phase I, 192 participants were randomized with varying doses of 2 μg, 4 μg, or 8 μg/dose or a placebo, and they received the same as a second dose 28 days later. Approximately 29% of participants reported at least 1 adverse event, most commonly fever, and neutralizing antibody titers were reported for all doses. In the phase II trial, 482 participants were enrolled (3:1, vaccine:placebo). Participants in the vaccine condition received either a single 8 μg dose or a double immunization of a 4 μg/dose that was administered 14, 21, or 28 days post the prime dose. Participants in the placebo condition received the placebo on one of the same four schedules. The vaccine appeared well-tolerated, with 23% reporting at least one adverse reaction characterized as mild to moderate. It was reported that all participants had a humoral immune response to the vaccines by day 42 but that the double immunization dosing regimen of 4 μg/dose achieved higher neutralizing antibody titers than a single dose of 8 μg and that the highest response was seen in the double-immunization regimen when at least 21 days separated the two doses [[81](#ref-fPGgVKYL)]. Similar findings were reported in another phase I/II trial published by the same authors [[85](#ref-yN5KOfvE)].

## 1.7 Protein Subunit Vaccines

Several different technologies are used to develop vaccines in this category. Proteins can be grown in yeast and then harvested, as they are culturable devoid of animal-derived growth factors. Indeed, the vaccine industry has previously mostly used Pichia pastoris yeast as the expression system [[45](#ref-7RHpaAHu)]. However, in recent years insect cells have also been utilized [[108](#ref-1FfwyYaj7),[147](#ref-Qk33ZrIC),[349](#ref-2Lol7zTw)]. Other protein subunit vaccines utilize virus-like particles (VLPs), which share the conformation of a virus’s capsid, thereby acting as an antigen, but lack the replication machinery [[111](#ref-lH2HMMZi)]. VLPs are often synthesized using nanotechnology [[350](#ref-OoS5TU81)].

### 1.7.1 Novavax NVX-CoV2373

Novavax-CoV2373 is a protein nanoparticle vaccine candidate against SARS-CoV-2. The vaccine is constructed from a mutated SARS-CoV-2 spike protein in combination with a specialized adjuvant to elicit an immune response against SARS-CoV-2. The spike protein is recombinantly expressed in Sf9 insect cells [[147](#ref-Qk33ZrIC)], which have previously been used for several other FDA-approved protein therapeutics [[148](#ref-RQR2sOmx)]. The expressed spike protein contains mutations in the furin cleavage site (682-RRAR-685 to 682-QQAQ-685) to avoid cleavage of the spike protein as well as two proline substitutions (K986P and V987P) to improve thermostability [[147](#ref-Qk33ZrIC)]. The improved stability caused by the proline substitutions is particularly critical to facilitating global distribution, particularly to regions where local refrigerator/freezer capacities are limited. Importantly, these amino acid substitutions did not affect the ability of the spike protein to bind the hACE2 receptor (the target receptor of SARS-CoV-2 spike protein). The Novavax-CoV2373 vaccine candidate uses a proprietary, saponin-based Matrix-MTM adjuvant that contains two different 40nm-sized particles formed by formulating purified saponin with cholesterol and phospholipids [[351](#ref-1F52Wz7mx)]. In preclinical models, the use of the Matrix-M adjuvant potentiated the cellular and humoral immune responses to influenza vaccines [[351](#ref-1F52Wz7mx),[352](#ref-scwOT7dw),[353](#ref-aD5iMC0Q),[354](#ref-twmXSpc9)]. Importantly, Matrix-M adjuvant-containing vaccines have shown acceptable safety profiles in human clinical trials [[355](#ref-jVCL0201)].

In preclinical mouse models, Novavax-CoV2373 elicited high anti-spike IgG titers 21-28 days post-vaccination that could neutralize the SARS-CoV-2 virus and protect the animals against virus challenge [[147](#ref-Qk33ZrIC)]. Antibody titers were significantly elevated in groups receiving the vaccine with the Matrix-M adjuvant compared to the groups without adjuvant. Novavax-CoV2373 was able to induce a multifunctional CD4/CD8 T-cell responses and generate high frequencies of follicular helper T-cells and B-cell germinal centers after vaccination. These findings were subsequently evaluated in a baboon primate model, in which Novavax-CoV2373 also elicited high antibody titers against the SARS-CoV-2 spike protein, as well as an antigen specific T-cell response. Based on this data Novavax initiated a Phase 1/2 clinical trial to evaluate the safety and immunogenicity of Novavax-CoV2373 with Matrix-M [[149](#ref-dMLXxGAI),[356](#ref-Nq0cimEs)].

The phase I/II trial was a randomized, placebo-controlled study with 131 healthy adult participants in 5 treatment arms [[149](#ref-dMLXxGAI)]. Participants that received the recombinant SARS-CoV-2 vaccine with or without the Matrix-M adjuvant got two injections, 21 days apart. Primary outcomes that were assessed include reactogenicity, lab-values (serum chemistry and hematology), and anti-spike IgG levels. Secondary outcomes measured included virus neutralization, T-cell responses, and unsolicited adverse events. The authors reported that no serious treatment-related adverse events occurred in any of the treatment arms. Reactogenicity was mostly absent and of short duration. The two-dose vaccine regimen induced anti-spike IgG levels and neutralizing antibody-titers exceeding those in the convalescent plasma of symptomatic patients. In line with the preclinical studies, the use of Matrix-M adjuvant further increased anti-spike immunoglobulin levels and induced a Th1 response. The outcomes of this trial suggest that Novavax-CoV2373 has an acceptable safety profile and is able to induce a strong immune response with high neutralizing antibody titers. The phase II component of this phase I/II trial was recently uploaded to an open-access repository [[357](#ref-UJnnQNkx)]. This part of the trial was designed to identify which dosing regimen should move forward into late phase clinical trials. Both younger (18-59 years) and older patients (60-84 years) were randomly assigned to receive either 5 μg or 25 μg Novavax-CoV2373 or placebo in two doses, 21 days apart. In line with the phase I data, reactogenicity remained mild to moderate and of short duration. Both dose levels were able to induce high anti-spike IgG titers as well as neutralizing antibody responses after the second dose. Based on both safety and efficacy data, the 5 μg dosing regimen was selected as the optimal dose regiment for the ongoing phase III trial. Although the phase III trial data has not been published yet, Novavax announced an efficacy of 89.3% based on their phase 3 trial in the UK and South Africa. This trial included over 15,000 participants in the UK and 4,000 participants in South Africa with occurrence of a PCR-confirmed symptomatic case as the primary endpoint. In the first interim analysis (U.K.), 56 cases of COVID-19 were observed in the placebo group compared to 6 cases in the treatment group. Importantly, the vaccine candidate also shows significant clinical efficacy against the prevalent UK and South African variants. The company has also initiated the development of new constructs to select candidates that can be used as a booster against new strains and plans to initiate clinical trials for these new constructs in the second quarter of 2021.

The primary endpoint of the trial was the occurrence or absence of PCR-confirmed, symptomatic mild, moderate or severe COVID-19 from 7 days after the second dose onward. Side effects were monitored in 2,310 participants and were generally considered mild, with low incidences of headache, muscle pain, and fatigue.

### 1.7.2 Protein Subunit Vaccine Development Programs Prior to SARS-CoV-2

Another set of studies has examined the immunogenicity of a SARS-CoV-1 RBD fused with IgG1 Fc. This recombinant fusion protein could induce a robust long-lasting neutralizing antibody and cellular immune response that protected mice from SARS-CoV-1 [[45](#ref-7RHpaAHu),[115](#ref-cLAQnckq),[116](#ref-1EirBATaN)]. While there have been other potential protein subunit vaccines for SARS-CoV-1 investigated *in vivo* [[45](#ref-7RHpaAHu),[125](#ref-9Zv0eLa9)], none of these candidates have successfully completed clinical trials, more than likely due to the fact that the SARS-CoV-1 epidemic mostly ended by May 2004, and there was thus less of a demand or funding for SARS-CoV-1 vaccine research.

Similar vaccine candidates have emerged that target the RBD found in the S1 subunit of the trimeric MERS-CoV S protein, which binds to dipeptidyl-peptidase 4 (DPP4 also known as hCD26), the entry point through which MERS-CoV infects cells [[358](#ref-yoFGwkUO),[359](#ref-KZFnwRIN),[360](#ref-YZcHzPcs)]. After initially determining that an RBD subunit candidate (S377-588-Fc) could elicit neutralizing antibodies [[361](#ref-GFWQw4mi)], a study in mice determined that the administration of three sequential doses of RBD-Fc vaccine coupled with MF59, a squalene immunogenic adjuvant, induced humoral and systemic immunity in mice [[362](#ref-SF030Zqn)]. Mice that had been transduced with Ad5-hCD26 and subsequently challenged with MERS-CoV five days later did not show evidence of viral infection in the lungs versus control mice at ten days post vaccination [[362](#ref-SF030Zqn)]. Other variations of this vaccine approach include a stable S trimer vaccine whereby proline-substituted variants of S2 can maintain a stable prefusion conformation of the S2 domain [[45](#ref-7RHpaAHu)]. This approach leads to broad and potent neutralizing antibodies [[45](#ref-7RHpaAHu)]

### 1.7.3 ZF2001

Phase I/II trial

## 1.8 SARS-CoV-2 Evolution and Vaccine Efficacy

### 1.8.1 Delta Variant and Ct

One preprint [[280](#ref-e2Qnnj6R)] analyzed a retrospective cohort of patients in Singapore who contracted COVID-19 from April to June of 2021.

This study focused on those who were confirmed or inferred to have been infected by the Delta variant of concern and its aim was to analyze virological kinetics. They identified 218 cases, 71 (33%) of whom were fully vaccinated with either the Pfizer/BioNTech or Moderna mRNA vaccines, 13 (6%) of whom had received only one dose or had received the second dose less than two weeks prior to infection, and four (2%) of whom had received a vaccine developed with another technology. Unvaccinated patients were more likely to be symptomatic or to progress to severe COVID-19 and showed more symptoms than vaccinated patients, despite the higher age of the vaccinated cohort. Ct was assessed over disease course, although the specific procedures for when additional RT-PCR was conducted is not clear; however, it is stated that the data was smoothed based on day of illness. There was no significant difference in median Ct in the initial samples taken from fully vaccinated and unvaccinated patients, but Ct increased (signifying reduced viral load) more rapidly in fully vaccinated patients. Like most analyses analyzing Ct [[9](#ref-GdZc4Yyd)], this study does not provide the data to make conclusions about contagiousness, as the samples were not cultured. All the same, these findings do suggest that vaccinated individuals may be able to clear the infection more quickly.

A second analysis was based in a county of Wisconsin, USA during summer 2021, when the Delta variant was known to be the dominant variant in the region [[281](#ref-N5OXLf7V)]. According to Our World in Data, at the beginning of the study, 49.3% of residents of Dane County were fully vaccinated, with this number rising to 51.4% by the end of the study , although an earlier version of the preprint reported the vaccination rate in Dane County as 67.4%. They identified no significant differences in Ct among fully vaccinated and unvaccinated cases. The Ct thresholds reported were consistent with contagiousness as evaluated in other studies, and in the present study, SARS-CoV-2 could be cultured from 51 of 55 samples with Ct less than 25. This study was not longitudinal, but the timing of testing relative to symptom onset between symptomatic vaccinated and unvaccinated patients. The findings of this study are therefore consistent with the idea that vaccinated people are less likely to contract symptomatic or severe COVID-19, but in cases of breakthrough infection, are still likely to be able to transmit SARS-CoV-2 to others.

## 1.9 Complementary Approaches to Vaccine Development

A complementary approach to other vaccine development programs that is being investigated explores the potential for vaccines that are not made from the SARS-CoV-2 virus to confer what has been termed trained immunity. In a recent review [[363](#ref-103fS7Kz2)], trained immunity was defined as forms of memory that are temporary (e.g., months or years) and reversible. It is induced by exposure to whole-microorganism vaccines or other microbial stimuli that generates heterologous protective effects. Trained immunity can be displayed by innate immune cells or innate immune features of other cells, and it is characterized by alterations to immune responsiveness to future immune challenges due to epigenetic and metabolic mechanisms. These alterations can take the form of either an increased or decreased response to immune challenge by a pathogen. Trained immunity elicited by non-SARS-CoV-2 whole-microorganism vaccines could potentially improve SARS-CoV-2 susceptibility or severity [[364](#ref-Vu1VILWK)].

One type of stimulus which research indicates can induce trained immunity is bacillus Calmette-Guerin (BCG) vaccination. BCG is an attenuated form of bacteria *Mycobacterium bovis*. The vaccine is most commonly administered for the prevention of tuberculosis in humans. Clinical trials in non-SARS-CoV-2-infected adults have been designed to assess whether BCG vaccination could have prophylactic effects against SARS-CoV-2 by reducing susceptibility, preventing infection, or reducing disease severity. A number of trials are now evaluating the effects of the BCG vaccine or the related vaccine VPM1002 [[294](#ref-9m3rP633),[295](#ref-xdqxBruc),[364](#ref-Vu1VILWK),[365](#ref-y9IYdfM3),[366](#ref-962rELVS),[367](#ref-EuwTWcPi),[368](#ref-dQtUeruv),[369](#ref-DjXsPR8O),[370](#ref-10OE6y3Pv),[371](#ref-86OjIybR),[372](#ref-ITO15LIz),[373](#ref-VkZGZxLn),[374](#ref-13JVjMfQI),[375](#ref-nk2MVsld),[376](#ref-1E2t9tr8h)].

The ongoing trials are using a number of different approaches. Some trials enroll healthcare workers, other trials hospitalized elderly adults without immunosuppression who get vaccinated with placebo or BCG at hospital discharge, and yet another set of trials older adults (>50 years) under chronic care for conditions like hypertension and diabetes. One set of trials, for example, uses time until first infection as the primary study endpoint; more generally, outcomes measured in some of these trials are related to incidence of disease and disease severity or symptoms. Some analyses have suggested a possible correlation at the country level between the frequency of BCG vaccination (or BCG vaccination policies) and the severity of COVID-19 [[364](#ref-Vu1VILWK)]. Currently it is unclear whether this correlation has any connection to trained immunity. Many possible confounding factors are also likely to vary among countries, such as age distribution, detection efficiency, stochastic epidemic dynamic effects, differences in healthcare capacity over time in relation to epidemic dynamics, and these have not been adequately accounted for in current analyses. It is unclear whether there is an effect of the timing of BCG vaccination, both during an individual’s life cycle and relative to the COVID-19 pandemic. Additionally, given that severe SARS-CoV-2 may be associated with a dysregulated immune response, it is unclear what alterations to the immune response would be most likely to be protective versus pathogenic (e.g., [[364](#ref-Vu1VILWK),[377](#ref-i5k18bpX),[378](#ref-1GnFL9zeN),[379](#ref-1228YjPRv)]). The article [[364](#ref-Vu1VILWK)] proposes that trained immunity might lead to an earlier and stronger response, which could in turn reduce viremia and the risk of later, detrimental immunopathology. While trained immunity is an interesting possible avenue to complement vaccine development efforts through the use of an existing vaccine, additional research is required to assess whether the BCG vaccine is likely to confer trained immunity in the case of SARS-CoV-2.

## 1.10 Viral evolution and vaccine protection

With these vaccines in place, one concern is how the virus’s continued evolution will affect their efficacy. Since the start of this pandemic, we have already seen multiple variants emerge: B.1.1.7, which emerged in the UK, B.1.351, which emerged in South Africa, and P.1, which emerged in Brazil.

Viruses evolve or mutate at different rates. Mutation rate is measured as the number of substitutions per nucleotide per cell infected (μs/n/c) [[380](#ref-4sZmtyNk)]. RNA viruses tend to have mutation rates between 10-6 to 10-4 [[380](#ref-4sZmtyNk)]. As a reference, influenza A virus has a mutation rate of 10-5, whereas the mutation rate of SARS-CoV-2 is lower, with the mutation rate estimated at 10-6 [[381](#ref-vESqa6V0)]. The accumulation of mutations allows the virus to escape recognition by the immune system [[382](#ref-2pzbGZvL)].

The efficacy of vaccines depends on their ability to train the immune system to recognize the virus. Therefore, viruses can develop resistance to vaccines through the accumulation of mutations that affect recognition. The lower mutation rate of SARS-CoV-2 suggests the possibility of SARS-CoV-2 vaccines having a more long-lasting effect compared to vaccines targeting the influenza A virus.

The current SARS-CoV-2 vaccines in distribution have been reported to provide similar efficacy against the B.1.1.7 variant compared to the variants common at the time they were developed but reduced efficacy against the B.1.351 variant [[383](#ref-LxJvckNs)]. Pfizer and Moderna announced that they are working on developing a booster shot to improve efficacy against the B.1.351 variant [[384](#ref-ZxfNX9xk)]. The WHO continues to monitor the emergence of variants and their impact on vaccine efficacy [[385](#ref-lY0XUlUp)]. Previous research in the computational prediction of the efficacy of vaccines targeting the influenza A virus might complement efforts to monitor these types of viral outbreaks [[386](#ref-YlAWEwlx)]. To adapt, future vaccines may need to account for multiple variants and strains of SARS-CoV-2, and booster shots may be required [[387](#ref-180UFKjJ2)].

## 1.11 Global Vaccine Status and Distribution

The unprecedented development of COVID-19 vaccines in under a year since the beginning of the pandemic now requires rapid global vaccine production and distribution plans. The development of vaccines is costly and complicated, but vaccine distribution can be just as challenging. Logistical considerations such as transport, storage, equipment (e.g., syringes), the workforce to administer the vaccines, and a continual supply from the manufacturers to meet global demands all must be accounted for and will vary globally due to economic, geographic, and sociopolitical reasons [[388](#ref-RG0vzlcE),[389](#ref-19CWe6pdS),[390](#ref-d0kUYq5Z)]. Deciding on the prioritization and allocation of the COVID-19 vaccines is also a challenging task due to ethical and operational considerations. Various frameworks, models, and methods have been proposed to tackle these issues with many countries, regions or states as is the case in the U.S., devising their own distribution and administration plans [[391](#ref-S8WhufUV),[392](#ref-dLbKv1xi),[393](#ref-jbpdQdOw),[394](#ref-z5c17nGB),[395](#ref-s2zZd6pb)]. The majority of the distribution plans prioritize offering vaccines to key workers such as health care workers, and those who are clinically vulnerable such as the elderly, the immunocompromised, and individuals with comorbidities, before targeting the rest of the population, who are less likely to experience severe outcomes from COVID-19 [[396](#ref-sEyIoYCS)]. As of March 6th, 2021, approximately 319 million vaccine doses have been administered in at least 118 countries worldwide using 10 different vaccines [[397](#ref-dfl5iCJI),[398](#ref-DQmAgN0V)]. The global vaccination rate is currently ~8.1 million doses per day, which at the current rate would take almost 4 years to vaccinate 75% of the world’s population according to media estimates of a two-dose regimen [[398](#ref-DQmAgN0V)]. Vaccine production and distribution varies from region to region and seems to depend on the availability of the vaccines and potentially a country’s resources and wealth [[399](#ref-kL8PlRJu)].

In North America, the majority of vaccines distributed until March 2021 have been produced by Pfizer-BioNTech and Moderna. In Canada, the vaccine approval process is conducted by Health Canada, which uses a fast-tracked process whereby vaccine producers can submit data as it becomes available to allow for rapid review. An approval may be granted following reviews of the available phase III clinical data. This is followed by a period of pharmacovigilance in the population using their post-market surveillance system, which will monitor the long-term safety and efficacy of any vaccines [[400](#ref-41tJkg7h),[401](#ref-YPaDf9jp)]. Health Canada has authorized the use of the Pfizer (December 9th, 2020), Moderna (December 23rd, 2020), Oxford-AstraZeneca (February 26th, 2021), and the Janssen (March 5th, 2021) vaccines, and the Novavax Inc vaccine is also under consideration [[402](#ref-15t1ePH1z)]. While Canada initially projected that by the end of September 2021 a vaccine would be available for all Canadian adults, they now predict that it may be possible earlier as more vaccines have been approved and become available [[403](#ref-fQM1moSe)].

In the U.S., vaccines are required to have demonstrated safety and efficacy in phase III trials before manufacturers apply for an emergency use authorization (EUA) from the FDA. If an EUA is granted, an additional evaluation of the safety and efficacy of the vaccines is conducted by the CDC’s Advisory Committee on Immunization Practices (ACIP) who also provide guidance on vaccine prioritization. On December 1st, 2020, ACIP provided an interim phase 1a recommendation that healthcare workers and long-term care facility residents should be the first to be offered any vaccine approved [[404](#ref-18BMz232x)]. This was shortly followed by an EUA on December 11th, 2020 for the use of the Pfizer-BioNTech COVID vaccine [[405](#ref-17wU8KTSP)], which was distributed and administered to the first healthcare workers on December 14th, 2020 [[406](#ref-123cVqUNO)]. Shortly thereafter, an EUA for the Moderna vaccine was issue on December 18th, 2020 [[407](#ref-7yAHeCqZ)]. On December 20th, 2020, ACIP updated their initial recommendations to suggest that vaccinations should be offered to people aged 75 years old and older and to non-healthcare frontline workers in phase 1b [[408](#ref-Y3jvGtR9)]. On the same date, it was recommended that phase 1c should include people aged 65-74 years old, individuals between the ages of 16-74 years old at high-risk due to health conditions, and essential workers ineligible in phase 1b [[408](#ref-Y3jvGtR9)]. On the following day, December 21st, 2020, the first Moderna vaccines used outside of clinical trials were administered to American healthcare workers, which was the same day that President-elect Biden and Dr. Biden received their first doses of the Pfizer-BioNTech vaccine live on television to instill confidence in the approval and vaccination process [[409](#ref-f5yIh2Xp)].

On February 27th, 2020, the FDA issued an EUA for the Janssen COVID-19 Vaccine [[410](#ref-BG7N9ETs)]. This was followed by an update on recommendations by ACIP for the use of the Janssen COVID-19 vaccine for those over 18 years old [[411](#ref-yNaiGtW1)]. The Janssen vaccine was first distributed to healthcare facilities on March 1st, 2021. On March 12, 2021, the WHO added the Janssen vaccine to the list of safe and effective emergency tools for COVID-19 [[412](#ref-Vd1wOy6d)]. While the CDC’s ACIP can provide recommendations, it is up to the public health authorities of each state, territory, and tribe to interpret the guidance and determine who will be vaccinated first [[413](#ref-1CcsUnCiw)]. Prior to distribution of the Janssen vaccine, over 103 million doses of the Moderna and Pfizer-BioNTech vaccines were delivered across the U.S., with almost 79 million doses administered. Of the total population, 15.6% have received at least one dose and 7.9% have received a second dose of either the Moderna (~38.3 million) or the Pfizer-BioNTech (~40.2 million) vaccines by February 28th, 2021 [[246](#ref-1Bv67ENp2)/#vaccinations]. President Biden’s administration has predicted that by the end of May 2021 there may be enough vaccine supply available for all adults in the U.S. [[414](#ref-ZkZ6ToLh),[415](#ref-13bndHWdk)]. However, vaccine production, approval, and distribution was not straightforward in the U.S., as information was initially sparse and the rollout of vaccines was complicated by poor planning and leadership due to political activities prior to the change of administration in January 2021 [[416](#ref-XOLE6iJT)]. These political complications highlight the importance of the transparent vaccine approval process conducted by the FDA [[417](#ref-1Bgnim0gX)].

Outside the U.S., the Moderna and Pfizer-BioNTech vaccines have been administered in 29 and 69 other countries, respectively, mainly in Europe and North America [[397](#ref-dfl5iCJI)]. The Janssen vaccine has so far only been administered in South Africa and the U.S. [[397](#ref-dfl5iCJI),[418](#ref-I0vakLIc)], but it has also been approved in Bahrain, the European Union (E.U.), Iceland, Liechtenstein, and Norway [[72](#ref-wByD9WaX)]. On March 11th, 2021, Johnson & Johnson received approval from the European Medicines Agency (EMA) for conditional marketing authorization of their vaccine [[419](#ref-17BEDzTkD)]. Notably, on March 2nd, 2021, rivals Johnson & Johnson and Merck announced that they entered an agreement to increase production of the Janssen vaccine to meet global demand [[420](#ref-hHW8U8rE)].

The U.K. was the first country to approve use of the Pfizer-BioNTech vaccine on December 2nd, 2020 [[421](#ref-133HGZMEL)], and it was later approved by EMA on December 21st, 2020 [[422](#ref-G6V3FR6V)]. The U.K. was also the first to administer the Pfizer-BioNTech vaccine, making it the first COVID-19 vaccine supported by phase III data to be administered outside of clinical trials on December 8th, 2020. The Oxford-AstraZeneca vaccine, was approved by the Medicines and Healthcare Products Regulatory Agency (MHRA) in the U.K. and by EMA in the E.U. on December 30th (2020) [[423](#ref-1HIxYDTsj)] and January 29th (2021) [[424](#ref-bbw8sMvc)] respectively. The Oxford-AstraZeneca vaccine was first administered in the UK on January 4th, 2021 [[425](#ref-q1Ui5Fm8)], and it is now being used in 53 countries in total, including Brazil, India, Pakistan, Mexico, and spanning most of Europe [[397](#ref-dfl5iCJI)]. The Moderna vaccine was authorized for use in the E.U. by EMA on January 6th, 2021 [[426](#ref-JPSLcRBY)] and in the U.K. by MHRA on January 8th, 2021 [[427](#ref-k9X9pXJe)]. As of March 5th, 2021, 22 million people in the U.K. had received at least one vaccine dose [[146](#ref-cWMPXfju)].

While the Pfizer-BioNTech vaccine was the first to be distributed following phase III clinical trials, the first COVID-19 vaccine to be widely administered to people prior to the completion of phase III clinical trials was Sputnik V. Sputnik V was administered to as many as 1.5 million Russians by early January [[212](#ref-X5LkVfY6)] due to the establishment of mass vaccination clinics in December 2020, prior to which only approximately 100,000 Russians had already been vaccinated [[428](#ref-uvQMgFXB),[429](#ref-Vwv7l7Hd)/?sh=50650e4e62e1]. Doses of Sputnik V have also been distributed to other parts of Europe, such as Belarus, Bosnia-Herzegovina, Hungary, San Marino, Serbia, and Slovakia [[213](#ref-16LczMwFO),[214](#ref-Z0V7NK7Y),[215](#ref-16GYKbrOq)], with the Czech Republic and Austria also having expressed interest in its procurement [[216](#ref-125VEHWS7)]. Hungary was the first E.U. member country to approve and distribute Sputnik V outside of Russia [[216](#ref-125VEHWS7)], despite the EMA stating that they had neither approved nor received a request for approval of Sputnik V [[430](#ref-P6x0Qy6s)]. Hungary is also in talks with China to procure the Sinopharm vaccines, which have been approved by Hungarian health authorities but also have not received approval by EMA in the E.U. [[216](#ref-125VEHWS7)]. In Latin America, production facilities in both Brazil and Argentina will allow for increased production capacity of Sputnik V and doses have been distributed to Mexico, Argentina, Bolivia, Nicaragua, Paraguay, and Venezuela [[431](#ref-ID8IywJM)]. Guinea was the first African nation to administer Sputnik V in December 2020, and the Central African Republic, Zimbabwe, and the Ivory Coast have all registered their interest in purchasing doses of the vaccine [[431](#ref-ID8IywJM)]. In the Middle East, Iran has received its first doses of Sputnik V and the United Arab Emirates is conducting phase III trials [[431](#ref-ID8IywJM)]. In Asia, while China’s vaccine candidates are favored, the Philippines, Nepal, and Uzbekistan have sought Sputnik V doses [[432](#ref-37uTx4hs)]. In total, the RDIF claims to have received orders totalling 1.2 billion doses by over 50 countries worldwide [[432](#ref-37uTx4hs)] and at least 18 countries are currently administering Sputnik V around the globe [[397](#ref-dfl5iCJI)]. Sputnik V has been an attractive vaccine for many countries due to its relatively low price, high efficacy, and its favorable storage conditions. For some countries, Russia and China have also been more palatable politically than vaccine suppliers in the West [[431](#ref-ID8IywJM),[433](#ref-FAQXPsyc)]. For others, the delays in the distribution of the other, more-favored candidates has been a motivating factor for pursuing the Sputnik V and Chinese alternatives [[214](#ref-Z0V7NK7Y),[433](#ref-FAQXPsyc)]. Additionally, Germany has stated that if Sputnik V were approved by EMA, it would be considered by the E.U. [[434](#ref-zCPl6A82)]. Russia is developing other vaccine candidates and has approved a third vaccine, CoviVac, which is an inactivated vaccine produced by the Chumakov Centre in Moscow, despite the fact the clinical trials have yet to begin [[435](#ref-hpScvlYg)].

In Asia, China and India are the main COVID-19 vaccination developers and providers. In India, the Covaxin vaccine produced by Bharat Biotech received emergency authorization on January 3rd, 2021, despite the lack of phase III data until March 3rd [[299](#ref-Ks3L7qHG)]. Following the release of the phase III data indicating 81% efficacy, Zimbabwe authorized the use of Covaxin [[301](#ref-13yEnvOyP)]. In February, 2021, Bharat Biotech received approval from Indian officials to commence a phase I study of an intranasal chimpanzee-adenovirus (ChAd) vectored SARS-CoV-2-S vaccine called BBV154 [[436](#ref-P9mD7Gc9)]. Notably, Novavax has signed an agreement with the Serum Institute of India allowing them to produce up to 2 billion doses a year [[437](#ref-e8pnj0O3)]. Novavax has also signed agreements with the U.K., Canada, Australia, and South Korea [[438](#ref-X3fVa3P8)] and has projected that they will supply 1.1 billion doses to COVAX who will distribute the vaccines to countries with disadvantaged access to vaccine supplies [[72](#ref-wByD9WaX)]. India has vaccinated approximately 24 million people [[398](#ref-DQmAgN0V)]. This has been achieved by mainly using the AstraZeneca-University of Oxford vaccine, known as Covishield in India, which is also produced by the Serum Institute of India, and using India’s own Covaxin vaccine [[439](#ref-gsNWcXHn)]. India has also shipped approximately 58 million COVID-19 vaccines to 66 countries [[440](#ref-QRYET3sK)] Considering India produces approximately 60% of the world’s vaccines prior to the pandemic, it is no surprise that several other vaccine candidates are under development. These include ZyCov-Di, a DNA vaccine produced by Zydus Cadila, HGCO19, India’s first mRNA vaccine produced by Genova and HDT Biotech Corporation (of the U.S.), and the Bio E subunit vaccine produced by Biological E in collaboration with U.S.-based Dynavax and the Baylor College of Medicine [[439](#ref-gsNWcXHn)].

In China, the Sinopharm-Beijing Institute vaccine, the Sinopharm-Wuhan Institute of Biological Products vaccine, the Sinovac Biotech (CoronaVac) vaccine, and CanSino Biologics vaccine are the main vaccines being distributed. The Sinopharm-Beijing vaccine has been distributed to at least 16 countries. This vaccine is currently approved for use in Bahrain, China, and the United Arab Emirates, but has been granted emergency use in Argentina, Cambodia, Egypt, Guyana, Hungary, Iran, Iraq, Jordan, Nepal, Pakistan, Peru, Venezuela, and Zimbabwe, with limited use in both Serbia and the Seychelles [[441](#ref-rqDwcy2A)]. Indeed, Sinovac and Sinopharm have estimated that they will be able to produce 2 billion doses by the end of 2021, and they have been able to distribute vaccines as aid to the Philippines and Pakistan [[442](#ref-gdTtuj5e)]. In contrast, the Sinopharm-Wuhan vaccine, which has been approved for use in China since February 25th, 2021, has been distributed almost exclusively within China, with limited supplies distributed to the United Arab Emirates [[443](#ref-mR6133bK)]. On the same date, the CanSino vaccine was approved for use in China and has been granted emergency use in Mexico and Pakistan, which were two participating countries in the CanSino phase III trials [[444](#ref-4PSTgetR)]. However, the vaccine approval and distribution processes in China have come under increased scrutiny from other nations. China was criticized for administering vaccines to thousands of government officials and state-owned businesses in September 2020, prior to the completion of phase III clinical trials [[417](#ref-1Bgnim0gX)]. The behavior of Chinese officials has also come into question due to misinformation campaigns questioning the safety of Western vaccine candidates such as Moderna and Pfizer-BioNTech in a way that is intended to highlight the benefits of their own vaccine candidates [[442](#ref-gdTtuj5e)]. Furthermore, delays in vaccine distribution have also caused issues, particularly in Turkey where 10 million doses of Sinovac were due to arrive by December 2020, but instead only 3 million were delivered in early January [[442](#ref-gdTtuj5e)]. Similar delays and shortages of doses promised have been reported by officials in the Philippines, Egypt, Morocco, and the United Arab Emirates [[445](#ref-XJmfG8HD),[446](#ref-12zVLzkpB)]. This will be concerning to China who have vaccine contracts for millions of doses with Indonesia (>100 million), Brazil (100 million), Chile (60 million), Turkey (50 million), Egypt (40 million) and many others [[446](#ref-12zVLzkpB)]. As of September 2021, CoronaVac trials are now also being held in the Philippines and Hong Kong, bringing the total number of registered phase III trials investigating the safety and efficacy of CoronaVac to 9, with emergency use approval in 40 countries [[298](#ref-19z4gdhDS)]. However, concern has been raised about the efficacy of CoronaVac following reports that over 350 doctors became ill with COVID-19 in Indonesia despite being immunized with CoronaVac [[97](#ref-fs7G9HyV)].

Globally, North America currently leads the world vaccination rates (13.8 per 100 people) followed by Europe (8.2 per 100), South America (3.1 per 100), Asia (1.9 per 100), Africa (0.3 per 100), and Oceania (0.1 per 100) are trailing behind [[397](#ref-dfl5iCJI)]. Considering the wealthy nations of North America and Europe have secured most of the limited COVID-19 vaccine stocks [[447](#ref-1AvwH3T5y)], it is likely that low- and middle-income countries will face further competition with Western countries for vaccine availability. While South Africa and Zimbabwe have their own vaccination programs, many other African nations will be reliant on the COVID-19 Vaccines Global Access (COVAX) Facility, who have promised 600 million doses to the continent [[448](#ref-1EnpYQzIq)]. COVAX is a multilateral initiative as part of the Access to COVID-19 Tools (ACT) Accelerator coordinated by the WHO, Gavi The Vaccine Alliance, and the Coalition for Epidemic Preparedness Innovations (CEPI), the latter two of which are supported by the Bill and Melinda Gates Foundation. Their intention is to accelerate the development of COVID-19 vaccines, diagnostics, and therapeutics and to ensure the equitable distribution of vaccines to low- and middle-income countries [[449](#ref-3Gq7ETv7),[450](#ref-KzHIbPMY)]. COVAX invested in several vaccine programs to ensure they would have access to successful vaccine candidates [[451](#ref-1H0PiQpLz)]. The COVAX plan ensured that all participating countries would be allocated vaccines in proportion to their population sizes. Once each country has received vaccine doses to account for 20% of their population, the country’s risk profile will determine its place in subsequent phases of vaccine distribution. However, several limitations of this framework exist, including that the COVAX scheme seems to go against the WHO’s own ethical principles of human well-being, equal respect, and global equity, and that other frameworks might have been more suitable, as is discussed elsewhere [[452](#ref-12QaZb4si)]. Furthermore, COVAX is supposed to allow poorer countries access to affordable vaccines, but the vaccines are driven by publicly traded companies that are required to make a profit [[399](#ref-kL8PlRJu)]. In any case, COVAX provides access to COVID-19 vaccines that may otherwise have been difficult for some countries to obtain. COVAX aims to distribute 2 billion vaccine doses globally by the end of 2021 [[453](#ref-7dkwQDUf)]. COVAX may also receive additional donations of doses from Western nations who purchased surplus vaccines in the race to vaccinate their populations, which will be a welcome boost to the vaccination programs of low- and middle-income countries [[454](#ref-sr5oRBgc)]. As of March, 2021, 9 African countries have received vaccines and at least 11 other nations have begun vaccinations via COVAX, aid from other countries, or their own agreements with producers [[448](#ref-1EnpYQzIq),[455](#ref-2b6FdDOy)]. However, much further progress is required when only 0.3 per 100 people have been vaccinated in Africa [[397](#ref-dfl5iCJI)].

## 1.12 Discussion

Additionally, major advances in vaccines using mRNA and adenoviruses that have led to three vaccines becoming available or close to becoming available in late 2020.

Though some concerns remain about the duration of sustained immunity for convalescents, vaccine development efforts are ongoing and show initial promising results. The Moderna trial, for example, reported that the neutralizing activity in participants who received two doses of the vaccine was similar to that observed in convalescent plasma.

One of the two mRNA vaccines, Pfizer and BioNTech’s BNT162b2, has been issued an EUA for patients as young as 16 [[456](#ref-1DETimS2y)], while ModernaTX has begun a clinical trial to assess its mRNA vaccine in adolescents ages 12 to 18 [[457](#ref-eDdKGPvy)].

# 2 Additional Items

## 2.1 Competing Interests

| Author | Competing Interests | Last Reviewed |
| --- | --- | --- |

## 2.2 Author Contributions

| Author | Contributions |
| --- | --- |

## 2.3 Acknowledgements

We thank Nick DeVito for assistance with the Evidence-Based Medicine Data Lab COVID-19 TrialsTracker data. We thank Yael Evelyn Marshall who contributed writing (original draft) as well as reviewing and editing of pieces of the text but who did not formally approve the manuscript, as well as Ronnie Russell, who contributed text to and helped develop the structure of the manuscript early in the writing process and Matthias Fax who helped with writing and editing text related to diagnostics. We are also very grateful to James Fraser for suggestions about successes and limitations in the area of computational screening for drug repurposing. We are grateful to the following contributors for reviewing pieces of the text: Nadia Danilova, James Eberwine and Ipsita Krishnan.

## 2.4 References

1. **History of vaccination** Stanley Plotkin *Proceedings of the National Academy of Sciences* (2014-08-18) <https://doi.org/f6fcwk> DOI: [10.1073/pnas.1400472111](https://doi.org/10.1073/pnas.1400472111) · PMID: [25136134](https://www.ncbi.nlm.nih.gov/pubmed/25136134) · PMCID: [PMC4151719](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4151719)

2. **A strategic approach to COVID-19 vaccine R&amp;D** Lawrence Corey, John R Mascola, Anthony S Fauci, Francis S Collins *Science* (2020-05-29) <https://doi.org/ggwfck> DOI: [10.1126/science.abc5312](https://doi.org/10.1126/science.abc5312) · PMID: [32393526](https://www.ncbi.nlm.nih.gov/pubmed/32393526)

3. **Neutralizing Monoclonal Antibodies as Promising Therapeutics against Middle East Respiratory Syndrome Coronavirus Infection** Hui-Ju Han, Jian-Wei Liu, Hao Yu, Xue-Jie Yu *Viruses* (2018-11-30) <https://doi.org/ggp87v> DOI: [10.3390/v10120680](https://doi.org/10.3390/v10120680) · PMID: [30513619](https://www.ncbi.nlm.nih.gov/pubmed/30513619) · PMCID: [PMC6315345](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6315345)

4. **Developing Covid-19 Vaccines at Pandemic Speed** Nicole Lurie, Melanie Saville, Richard Hatchett, Jane Halton *New England Journal of Medicine* (2020-05-21) <https://doi.org/ggq8bc> DOI: [10.1056/nejmp2005630](https://doi.org/10.1056/nejmp2005630) · PMID: [32227757](https://www.ncbi.nlm.nih.gov/pubmed/32227757)

5. **Editorial: Reverse Vaccinology** Richard Moxon, Pedro A Reche, Rino Rappuoli *Frontiers in Immunology* (2019-12-03) <https://doi.org/gjjtwg> DOI: [10.3389/fimmu.2019.02776](https://doi.org/10.3389/fimmu.2019.02776) · PMID: [31849959](https://www.ncbi.nlm.nih.gov/pubmed/31849959) · PMCID: [PMC6901788](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6901788)

6. **Rapid response to an emerging infectious disease – Lessons learned from development of a synthetic DNA vaccine targeting Zika virus** Sagar B Kudchodkar, Hyeree Choi, Emma L Reuschel, Rianne Esquivel, Jackie Jin-Ah Kwon, Moonsup Jeong, Joel N Maslow, Charles C Reed, Scott White, JJoseph Kim, … Kar Muthumani *Microbes and Infection* (2018-12) <https://doi.org/gfrn5h> DOI: [10.1016/j.micinf.2018.03.001](https://doi.org/10.1016/j.micinf.2018.03.001) · PMID: [29555345](https://www.ncbi.nlm.nih.gov/pubmed/29555345) · PMCID: [PMC6593156](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6593156)

7. **Newer Vaccine Technologies Deployed to Develop COVID-19 Shot** Abby Olena *The Scientist Magazine* (2020-02-21) <https://www.the-scientist.com/news-opinion/newer-vaccine-technologies-deployed-to-develop-covid-19-shot-67152>

8. **DNA vaccines: ready for prime time?** Michele A Kutzler, David B Weiner *Nature Reviews Genetics* (2008-10) <https://doi.org/fvzwbs> DOI: [10.1038/nrg2432](https://doi.org/10.1038/nrg2432) · PMID: [18781156](https://www.ncbi.nlm.nih.gov/pubmed/18781156) · PMCID: [PMC4317294](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4317294)

9. **Pathogenesis, Symptomatology, and Transmission of SARS-CoV-2 through Analysis of Viral Genomics and Structure** Halie M Rando, Adam L MacLean, Alexandra J Lee, Ronan Lordan, Sandipan Ray, Vikas Bansal, Ashwin N Skelly, Elizabeth Sell, John J Dziak, Lamonica Shinholster, … Casey S Greene *mSystems* (2021-10-26) <https://pubmed.ncbi.nlm.nih.gov/34698547/> DOI: [10.1128/msystems.00095-21](https://doi.org/10.1128/mSystems.00095-21)

10. **Identification and Development of Therapeutics for COVID-19** Halie M Rando, Nils Wellhausen, Soumita Ghosh, Alexandra J Lee, Anna Ada Dattoli, Fengling Hu, James Brian Byrd, Diane N Rafizadeh, Ronan Lordan, Yanjun Qi, … Casey S Greene *mSystems* (2021-12-21) <https://pubmed.ncbi.nlm.nih.gov/34726496/> DOI: [10.1128/msystems.00233-21](https://doi.org/10.1128/mSystems.00233-21)

11. **Novel Coronavirus – China** <https://www.who.int/emergencies/disease-outbreak-news/item/2020-DON233>

12. **Safety and efficacy of the ChAdOx1 nCoV-19 vaccine (AZD1222) against SARS-CoV-2: an interim analysis of four randomised controlled trials in Brazil, South Africa, and the UK** Merryn Voysey, Sue Ann Costa Clemens, Shabir A Madhi, Lily Y Weckx, Pedro M Folegatti, Parvinder K Aley, Brian Angus, Vicky L Baillie, Shaun L Barnabas, Qasim E Bhorat, … Peter Zuidewind *The Lancet* (2021-01) <https://doi.org/fmq2> DOI: [10.1016/s0140-6736(20)32661-1](https://doi.org/10.1016/s0140-6736(20)32661-1) · PMID: [33306989](https://www.ncbi.nlm.nih.gov/pubmed/33306989) · PMCID: [PMC7723445](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7723445)

13. **The SARS-CoV-2 Spike Glycoprotein Biosynthesis, Structure, Function, and Antigenicity: Implications for the Design of Spike-Based Vaccine Immunogens** Liangwei Duan, Qianqian Zheng, Hongxia Zhang, Yuna Niu, Yunwei Lou, Hui Wang *Frontiers in Immunology* (2020-10-07) <https://doi.org/gjkthw> DOI: [10.3389/fimmu.2020.576622](https://doi.org/10.3389/fimmu.2020.576622) · PMID: [33117378](https://www.ncbi.nlm.nih.gov/pubmed/33117378) · PMCID: [PMC7575906](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7575906)

14. **SARS-CoV-2 vaccines in development** Florian Krammer *Nature* (2020-09-23) <https://doi.org/ghdprn> DOI: [10.1038/s41586-020-2798-3](https://doi.org/10.1038/s41586-020-2798-3) · PMID: [32967006](https://www.ncbi.nlm.nih.gov/pubmed/32967006)

15. **An mRNA Vaccine against SARS-CoV-2 — Preliminary Report** Lisa A Jackson, Evan J Anderson, Nadine G Rouphael, Paul C Roberts, Mamodikoe Makhene, Rhea N Coler, Michele P McCullough, James D Chappell, Mark R Denison, Laura J Stevens, … John H Beigel *New England Journal of Medicine* (2020-11-12) <https://doi.org/d3tt> DOI: [10.1056/nejmoa2022483](https://doi.org/10.1056/nejmoa2022483) · PMID: [32663912](https://www.ncbi.nlm.nih.gov/pubmed/32663912) · PMCID: [PMC7377258](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7377258)

16. **BioRender** BioRender <https://biorender.com/>

17. **New Images of Novel Coronavirus SARS-CoV-2 Now Available | NIH: National Institute of Allergy and Infectious Diseases** <https://www.niaid.nih.gov/news-events/novel-coronavirus-sarscov2-images>

18. **Structural features of coronavirus SARS-CoV-2 spike protein: Targets for vaccination** Ariane Sternberg, Cord Naujokat *Life Sciences* (2020-09) <https://doi.org/gg4cmp> DOI: [10.1016/j.lfs.2020.118056](https://doi.org/10.1016/j.lfs.2020.118056) · PMID: [32645344](https://www.ncbi.nlm.nih.gov/pubmed/32645344) · PMCID: [PMC7336130](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7336130)

19. **Structure, Function, and Evolution of Coronavirus Spike Proteins** Fang Li *Annual Review of Virology* (2016-09-29) <https://doi.org/ggr7gv> DOI: [10.1146/annurev-virology-110615-042301](https://doi.org/10.1146/annurev-virology-110615-042301) · PMID: [27578435](https://www.ncbi.nlm.nih.gov/pubmed/27578435) · PMCID: [PMC5457962](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5457962)

20. **Pre-fusion structure of a human coronavirus spike protein** Robert N Kirchdoerfer, Christopher A Cottrell, Nianshuang Wang, Jesper Pallesen, Hadi M Yassine, Hannah L Turner, Kizzmekia S Corbett, Barney S Graham, Jason S McLellan, Andrew B Ward *Nature* (2016-03) <https://doi.org/f8b8zb> DOI: [10.1038/nature17200](https://doi.org/10.1038/nature17200) · PMID: [26935699](https://www.ncbi.nlm.nih.gov/pubmed/26935699) · PMCID: [PMC4860016](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4860016)

21. **Structure, Function, and Antigenicity of the SARS-CoV-2 Spike Glycoprotein** Alexandra C Walls, Young-Jun Park, MAlejandra Tortorici, Abigail Wall, Andrew T McGuire, David Veesler *Cell* (2020-04) <https://doi.org/dpvh> DOI: [10.1016/j.cell.2020.02.058](https://doi.org/10.1016/j.cell.2020.02.058) · PMID: [32155444](https://www.ncbi.nlm.nih.gov/pubmed/32155444) · PMCID: [PMC7102599](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7102599)

22. **The Architecture of Inactivated SARS-CoV-2 with Postfusion Spikes Revealed by Cryo-EM and Cryo-ET** Chuang Liu, Luiza Mendonça, Yang Yang, Yuanzhu Gao, Chenguang Shen, Jiwei Liu, Tao Ni, Bin Ju, Congcong Liu, Xian Tang, … Peijun Zhang *Structure* (2020-11) <https://doi.org/ghhwtg> DOI: [10.1016/j.str.2020.10.001](https://doi.org/10.1016/j.str.2020.10.001) · PMID: [33058760](https://www.ncbi.nlm.nih.gov/pubmed/33058760) · PMCID: [PMC7557167](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7557167)

23. **Structures and distributions of SARS-CoV-2 spike proteins on intact virions** Zunlong Ke, Joaquin Oton, Kun Qu, Mirko Cortese, Vojtech Zila, Lesley McKeane, Takanori Nakane, Jasenko Zivanov, Christopher J Neufeldt, Berati Cerikan, … John AG Briggs *Nature* (2020-08-17) <https://doi.org/d6sf> DOI: [10.1038/s41586-020-2665-2](https://doi.org/10.1038/s41586-020-2665-2) · PMID: [32805734](https://www.ncbi.nlm.nih.gov/pubmed/32805734) · PMCID: [PMC7116492](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7116492)

24. **Immunogenicity and structures of a rationally designed prefusion MERS-CoV spike antigen** Jesper Pallesen, Nianshuang Wang, Kizzmekia S Corbett, Daniel Wrapp, Robert N Kirchdoerfer, Hannah L Turner, Christopher A Cottrell, Michelle M Becker, Lingshu Wang, Wei Shi, … Jason S McLellan *Proceedings of the National Academy of Sciences* (2017-08-14) <https://doi.org/gbwk7p> DOI: [10.1073/pnas.1707304114](https://doi.org/10.1073/pnas.1707304114) · PMID: [28807998](https://www.ncbi.nlm.nih.gov/pubmed/28807998) · PMCID: [PMC5584442](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5584442)

25. **Mechanisms of Coronavirus Cell Entry Mediated by the Viral Spike Protein** Sandrine Belouzard, Jean K Millet, Beth N Licitra, Gary R Whittaker *Viruses* (2012-06-20) <https://doi.org/gbbktb> DOI: [10.3390/v4061011](https://doi.org/10.3390/v4061011) · PMID: [22816037](https://www.ncbi.nlm.nih.gov/pubmed/22816037) · PMCID: [PMC3397359](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3397359)

26. **Phylogenetic Analysis and Structural Modeling of SARS-CoV-2 Spike Protein Reveals an Evolutionary Distinct and Proteolytically Sensitive Activation Loop** Javier A Jaimes, Nicole M André, Joshua S Chappie, Jean K Millet, Gary R Whittaker *Journal of Molecular Biology* (2020-05) <https://doi.org/ggtxhr> DOI: [10.1016/j.jmb.2020.04.009](https://doi.org/10.1016/j.jmb.2020.04.009) · PMID: [32320687](https://www.ncbi.nlm.nih.gov/pubmed/32320687) · PMCID: [PMC7166309](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7166309)

27. **Structure-based design of prefusion-stabilized SARS-CoV-2 spikes** Ching-Lin Hsieh, Jory A Goldsmith, Jeffrey M Schaub, Andrea M DiVenere, Hung-Che Kuo, Kamyab Javanmardi, Kevin C Le, Daniel Wrapp, Alison G Lee, Yutong Liu, … Jason S McLellan *Science* (2020-09-18) <https://doi.org/gg8k5r> DOI: [10.1126/science.abd0826](https://doi.org/10.1126/science.abd0826) · PMID: [32703906](https://www.ncbi.nlm.nih.gov/pubmed/32703906) · PMCID: [PMC7402631](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7402631)

28. **Ad26 vector-based COVID-19 vaccine encoding a prefusion-stabilized SARS-CoV-2 Spike immunogen induces potent humoral and cellular immune responses** Rinke Bos, Lucy Rutten, Joan EM van der Lubbe, Mark JG Bakkers, Gijs Hardenberg, Frank Wegmann, David Zuijdgeest, Adriaan H de Wilde, Annemart Koornneef, Annemiek Verwilligen, … Hanneke Schuitemaker *npj Vaccines* (2020-09-28) <https://doi.org/ghjkr8> DOI: [10.1038/s41541-020-00243-x](https://doi.org/10.1038/s41541-020-00243-x) · PMID: [33083026](https://www.ncbi.nlm.nih.gov/pubmed/33083026) · PMCID: [PMC7522255](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7522255)

29. **Towards an understanding of the adjuvant action of aluminium** Philippa Marrack, Amy S McKee, Michael W Munks *Nature Reviews Immunology* (2009-04) <https://doi.org/drcwvf> DOI: [10.1038/nri2510](https://doi.org/10.1038/nri2510) · PMID: [19247370](https://www.ncbi.nlm.nih.gov/pubmed/19247370) · PMCID: [PMC3147301](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3147301)

30. **DAMP-Inducing Adjuvant and PAMP Adjuvants Parallelly Enhance Protective Type-2 and Type-1 Immune Responses to Influenza Split Vaccination** Tomoya Hayashi, Masatoshi Momota, Etsushi Kuroda, Takato Kusakabe, Shingo Kobari, Kotaro Makisaka, Yoshitaka Ohno, Yusuke Suzuki, Fumika Nakagawa, Michelle SJ Lee, … Hidetoshi Arima *Frontiers in Immunology* (2018-11-20) <https://doi.org/gfqq89> DOI: [10.3389/fimmu.2018.02619](https://doi.org/10.3389/fimmu.2018.02619) · PMID: [30515151](https://www.ncbi.nlm.nih.gov/pubmed/30515151) · PMCID: [PMC6255964](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6255964)

31. **Better Adjuvants for Better Vaccines: Progress in Adjuvant Delivery Systems, Modifications, and Adjuvant–Antigen Codelivery** Zhi-Biao Wang, Jing Xu *Vaccines* (2020-03-13) <https://doi.org/gg35vj> DOI: [10.3390/vaccines8010128](https://doi.org/10.3390/vaccines8010128) · PMID: [32183209](https://www.ncbi.nlm.nih.gov/pubmed/32183209) · PMCID: [PMC7157724](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7157724)

32. **Our Story** Moderna <https://www.modernatx.com/en-US/about-us/our-story?slug=about-us%2Four-story>

33. **The COVID-19 vaccine development landscape** Tung Thanh Le, Zacharias Andreadakis, Arun Kumar, Raúl Gómez Román, Stig Tollefsen, Melanie Saville, Stephen Mayhew *Nature Reviews Drug Discovery* (2020-04-09) <https://doi.org/ggrnbr> DOI: [10.1038/d41573-020-00073-5](https://doi.org/10.1038/d41573-020-00073-5) · PMID: [32273591](https://www.ncbi.nlm.nih.gov/pubmed/32273591)

34. **The history of the smallpox vaccine** Alexandra J Stewart, Phillip M Devlin *Journal of Infection* (2006-05) <https://doi.org/d455hw> DOI: [10.1016/j.jinf.2005.07.021](https://doi.org/10.1016/j.jinf.2005.07.021) · PMID: [16176833](https://www.ncbi.nlm.nih.gov/pubmed/16176833)

35. **“Variolation” and Vaccination in Late Imperial China, Ca 1570–1911** Angela Ki Che Leung *History of Vaccine Development* (2011) <https://doi.org/fftx2m> DOI: [10.1007/978-1-4419-1339-5\_2](https://doi.org/10.1007/978-1-4419-1339-5_2)

36. **The History Of Vaccines And Immunization: Familiar Patterns, New Challenges** Alexandra Minna Stern, Howard Markel *Health Affairs* (2005-05) <https://doi.org/dzcwg5> DOI: [10.1377/hlthaff.24.3.611](https://doi.org/10.1377/hlthaff.24.3.611) · PMID: [15886151](https://www.ncbi.nlm.nih.gov/pubmed/15886151)

37. **Equination (inoculation of horsepox): An early alternative to vaccination (inoculation of cowpox) and the potential role of horsepox virus in the origin of the smallpox vaccine** José Esparza, Livia Schrick, Clarissa R Damaso, Andreas Nitsche *Vaccine* (2017-12) <https://doi.org/gcsnbp> DOI: [10.1016/j.vaccine.2017.11.003](https://doi.org/10.1016/j.vaccine.2017.11.003) · PMID: [29137821](https://www.ncbi.nlm.nih.gov/pubmed/29137821)

38. **Live attenuated vaccines: Historical successes and current challenges** Philip D Minor *Virology* (2015-05) <https://doi.org/f7cnmj> DOI: [10.1016/j.virol.2015.03.032](https://doi.org/10.1016/j.virol.2015.03.032) · PMID: [25864107](https://www.ncbi.nlm.nih.gov/pubmed/25864107)

39. **Advances in mRNA Vaccines for Infectious Diseases** Cuiling Zhang, Giulietta Maruggi, Hu Shan, Junwei Li *Frontiers in Immunology* (2019-03-27) <https://doi.org/ggsnm7> DOI: [10.3389/fimmu.2019.00594](https://doi.org/10.3389/fimmu.2019.00594) · PMID: [30972078](https://www.ncbi.nlm.nih.gov/pubmed/30972078) · PMCID: [PMC6446947](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6446947)

40. **DNA Vaccine** Zhengrong Cui *Non-Viral Vectors for Gene Therapy, Second Edition: Part 2* (2005) <https://doi.org/dn299p> DOI: [10.1016/s0065-2660(05)54011-2](https://doi.org/10.1016/s0065-2660(05)54011-2) · PMID: [16096015](https://www.ncbi.nlm.nih.gov/pubmed/16096015) · PMCID: [PMC7119308](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7119308)

41. **Types of Vaccines – COVID19 Vaccine Tracker** <https://covid19.trackvaccines.org/types-of-vaccines/>

42. **A single-dose live-attenuated YF17D-vectored SARS-CoV-2 vaccine candidate** Lorena Sanchez-Felipe, Thomas Vercruysse, Sapna Sharma, Ji Ma, Viktor Lemmens, Dominique Van Looveren, Mahadesh Prasad Arkalagud Javarappa, Robbert Boudewijns, Bert Malengier-Devlies, Laurens Liesenborghs, … Kai Dallmeier *Nature* (2020-12-01) <https://doi.org/ghn8jk> DOI: [10.1038/s41586-020-3035-9](https://doi.org/10.1038/s41586-020-3035-9) · PMID: [33260195](https://www.ncbi.nlm.nih.gov/pubmed/33260195)

43. **Principles of Virology, Volume I: Molecular Biology** Jane Flint, Anna Marie Skalka, Glenn F Rall, Vincent R Racaniello *American Society of Microbiology* (2015-01-01) <https://doi.org/gmqjck> DOI: [10.1128/9781555818951](https://doi.org/10.1128/9781555818951)

44. **Vaccine Immunology** Claire-Anne Siegrist *Plotkin's Vaccines* (2018) <https://doi.org/gmqjcc> DOI: [10.1016/b978-0-323-35761-6.00002-x](https://doi.org/10.1016/b978-0-323-35761-6.00002-x)

45. **COVID-19: Coronavirus Vaccine Development Updates** Jing Zhao, Shan Zhao, Junxian Ou, Jing Zhang, Wendong Lan, Wenyi Guan, Xiaowei Wu, Yuqian Yan, Wei Zhao, Jianguo Wu, … Qiwei Zhang *Frontiers in Immunology* (2020-12-23) <https://doi.org/gkbs4k> DOI: [10.3389/fimmu.2020.602256](https://doi.org/10.3389/fimmu.2020.602256) · PMID: [33424848](https://www.ncbi.nlm.nih.gov/pubmed/33424848) · PMCID: [PMC7785583](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7785583)

46. **Griffith University researchers on the road to COVID-19 vaccine** Deborah Marshall <https://news.griffith.edu.au/2020/04/23/griffith-university-researchers-on-the-road-to-covid-19-vaccine/>

47. **Milken Institute’s COVID-19 Treatment and Vaccine Tracker tracks the development of treatments and vaccines for COVID-19 at covid-19tracker.milkeninstitute.org #COVID19 #coronavirus #COVID19treatment #COVID19vaccine @MilkenInstitute @FirstPersonSF** <https://covid-19tracker.milkeninstitute.org/>

48. **Scalable live-attenuated SARS-CoV-2 vaccine candidate demonstrates preclinical safety and efficacy** Ying Wang, Chen Yang, Yutong Song, JRobert Coleman, Marcin Stawowczyk, Juliana Tafrova, Sybil Tasker, David Boltz, Robert Baker, Liliana Garcia, … Steffen Mueller *Proceedings of the National Academy of Sciences* (2021-06-30) <https://doi.org/gmc76v> DOI: [10.1073/pnas.2102775118](https://doi.org/10.1073/pnas.2102775118) · PMID: [34193524](https://www.ncbi.nlm.nih.gov/pubmed/34193524) · PMCID: [PMC8307828](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8307828)

49. **A Lassa Fever Live-Attenuated Vaccine Based on Codon Deoptimization of the Viral Glycoprotein Gene** Yingyun Cai, Chengjin Ye, Benson Cheng, Aitor Nogales, Masaharu Iwasaki, Shuiqing Yu, Kurt Cooper, David X Liu, Randy Hart, Ricky Adams, … Luis Martínez-Sobrido *mBio* (2020-02-25) <https://doi.org/gnvf9q> DOI: [10.1128/mbio.00039-20](https://doi.org/10.1128/mbio.00039-20) · PMID: [32098811](https://www.ncbi.nlm.nih.gov/pubmed/32098811) · PMCID: [PMC7042690](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7042690)

50. **Recent Progress in Vaccine Development Against Chikungunya Virus** Shan Gao, Siqi Song, Leiliang Zhang *Frontiers in Microbiology* (2019-12-19) <https://doi.org/gh7rn6> DOI: [10.3389/fmicb.2019.02881](https://doi.org/10.3389/fmicb.2019.02881) · PMID: [31921059](https://www.ncbi.nlm.nih.gov/pubmed/31921059) · PMCID: [PMC6930866](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6930866)

51. **BCG-induced trained immunity: can it offer protection against COVID-19?** Luke AJ O’Neill, Mihai G Netea *Nature Reviews Immunology* (2020-05-11) <https://doi.org/ggvzp3> DOI: [10.1038/s41577-020-0337-y](https://doi.org/10.1038/s41577-020-0337-y) · PMID: [32393823](https://www.ncbi.nlm.nih.gov/pubmed/32393823) · PMCID: [PMC7212510](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7212510)

52. **Non-specific effects of BCG vaccine on viral infections** SJCFM Moorlag, RJW Arts, R van Crevel, MG Netea *Clinical Microbiology and Infection* (2019-12) <https://doi.org/ggq62z> DOI: [10.1016/j.cmi.2019.04.020](https://doi.org/10.1016/j.cmi.2019.04.020) · PMID: [31055165](https://www.ncbi.nlm.nih.gov/pubmed/31055165)

53. **Efficacy of Bacillus Calmette-Guérin vaccination against respiratory tract infections in the elderly during the Covid-19 pandemic** Simone JCFM Moorlag, Esther Taks, Thijs ten Doesschate, Thomas W van der Vaart, Axel B Janssen, Lisa Müller, Philipp Ostermann, Helga Dijkstra, Heidi Lemmers, Elles Simonetti, … Mihai G Netea *Clinical Infectious Diseases* (2022-03-05) <https://doi.org/gptcjh> DOI: [10.1093/cid/ciac182](https://doi.org/10.1093/cid/ciac182) · PMID: [35247264](https://www.ncbi.nlm.nih.gov/pubmed/35247264) · PMCID: [PMC8903481](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8903481)

54. **Replicating and non-replicating viral vectors for vaccine development** Marjorie Robert-Guroff *Current Opinion in Biotechnology* (2007-12) <https://doi.org/dgfz6w> DOI: [10.1016/j.copbio.2007.10.010](https://doi.org/10.1016/j.copbio.2007.10.010) · PMID: [18063357](https://www.ncbi.nlm.nih.gov/pubmed/18063357) · PMCID: [PMC2245896](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2245896)

55. **Vaccine Types** Office of Infectious Disease and HIV/AIDS Policy (OIDP) *HHS.gov* (2021-04-26) <https://www.hhs.gov/immunization/basics/types/index.html>

56. **Vero cell technology for rapid development of inactivated whole virus vaccines for emerging viral diseases** PNoel Barrett, Sara J Terpening, Doris Snow, Ronald R Cobb, Otfried Kistner *Expert Review of Vaccines* (2017-07-27) <https://doi.org/ggt7vf> DOI: [10.1080/14760584.2017.1357471](https://doi.org/10.1080/14760584.2017.1357471) · PMID: [28724343](https://www.ncbi.nlm.nih.gov/pubmed/28724343)

57. **Vaccine delivery: a matter of size, geometry, kinetics and molecular patterns** Martin F Bachmann, Gary T Jennings *Nature Reviews Immunology* (2010-10-15) <https://doi.org/fg5dx9> DOI: [10.1038/nri2868](https://doi.org/10.1038/nri2868) · PMID: [20948547](https://www.ncbi.nlm.nih.gov/pubmed/20948547)

58. **Animal models and vaccines for SARS-CoV infection** Anjeanette Roberts, Elaine W Lamirande, Leatrice Vogel, Jadon P Jackson, Christopher D Paddock, Jeannette Guarner, Sherif R Zaki, Timothy Sheahan, Ralph Baric, Kanta Subbarao *Virus Research* (2008-04) <https://doi.org/brrg6k> DOI: [10.1016/j.virusres.2007.03.025](https://doi.org/10.1016/j.virusres.2007.03.025) · PMID: [17499378](https://www.ncbi.nlm.nih.gov/pubmed/17499378) · PMCID: [PMC2323511](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2323511)

59. **Functional analysis of influenza-specific helper T cell clones in vivo. T cells specific for internal viral proteins provide cognate help for B cell responses to hemagglutinin.** PA Scherle, W Gerhard *Journal of Experimental Medicine* (1986-10-01) <https://doi.org/bp47qh> DOI: [10.1084/jem.164.4.1114](https://doi.org/10.1084/jem.164.4.1114) · PMID: [2944982](https://www.ncbi.nlm.nih.gov/pubmed/2944982) · PMCID: [PMC2188433](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2188433)

60. **Severe acute respiratory syndrome (SARS) coronavirus: application of monoclonal antibodies and development of an effective vaccine** Yasuko Tsunetsugu-Yokota, Kazuo Ohnishi, Toshitada Takemori *Reviews in Medical Virology* (2006) <https://doi.org/dskzwh> DOI: [10.1002/rmv.492](https://doi.org/10.1002/rmv.492) · PMID: [16518829](https://www.ncbi.nlm.nih.gov/pubmed/16518829) · PMCID: [PMC7169118](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7169118)

61. **A subcutaneously injected UV-inactivated SARS coronavirus vaccine elicits systemic humoral immunity in mice** N Takasuka *International Immunology* (2004-08-31) <https://doi.org/bkd6xq> DOI: [10.1093/intimm/dxh143](https://doi.org/10.1093/intimm/dxh143) · PMID: [15314040](https://www.ncbi.nlm.nih.gov/pubmed/15314040) · PMCID: [PMC7108621](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7108621)

62. **Learning from the past: development of safe and effective COVID-19 vaccines** Shan Su, Lanying Du, Shibo Jiang *Nature Reviews Microbiology* (2020-10-16) <https://doi.org/ghmtgp> DOI: [10.1038/s41579-020-00462-y](https://doi.org/10.1038/s41579-020-00462-y) · PMID: [33067570](https://www.ncbi.nlm.nih.gov/pubmed/33067570) · PMCID: [PMC7566580](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7566580)

63. **Immunodominant SARS Coronavirus Epitopes in Humans Elicited both Enhancing and Neutralizing Effects on Infection in Non-human Primates** Qidi Wang, Lianfeng Zhang, Kazuhiko Kuwahara, Li Li, Zijie Liu, Taisheng Li, Hua Zhu, Jiangning Liu, Yanfeng Xu, Jing Xie, … Gang Liu *ACS Infectious Diseases* (2016-03-30) <https://doi.org/ggrcdk> DOI: [10.1021/acsinfecdis.6b00006](https://doi.org/10.1021/acsinfecdis.6b00006) · PMID: [27627203](https://www.ncbi.nlm.nih.gov/pubmed/27627203) · PMCID: [PMC7075522](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7075522)

64. **Immunization with inactivated Middle East Respiratory Syndrome coronavirus vaccine leads to lung immunopathology on challenge with live virus** Anurodh Shankar Agrawal, Xinrong Tao, Abdullah Algaissi, Tania Garron, Krishna Narayanan, Bi-Hung Peng, Robert B Couch, Chien-Te K Tseng *Human Vaccines & Immunotherapeutics* (2016-06-07) <https://doi.org/gmkb76> DOI: [10.1080/21645515.2016.1177688](https://doi.org/10.1080/21645515.2016.1177688) · PMID: [27269431](https://www.ncbi.nlm.nih.gov/pubmed/27269431) · PMCID: [PMC5027702](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5027702)

65. **Single-Dose, Intranasal Immunization with Recombinant Parainfluenza Virus 5 Expressing Middle East Respiratory Syndrome Coronavirus (MERS-CoV) Spike Protein Protects Mice from Fatal MERS-CoV Infection** Kun Li, Zhuo Li, Christine Wohlford-Lenane, David K Meyerholz, Rudragouda Channappanavar, Dong An, Stanley Perlman, Paul B McCray Jr., Biao He *mBio* (2020-04-28) <https://doi.org/ggrzk2> DOI: [10.1128/mbio.00554-20](https://doi.org/10.1128/mbio.00554-20) · PMID: [32265331](https://www.ncbi.nlm.nih.gov/pubmed/32265331) · PMCID: [PMC7157776](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7157776)

66. **Safety, tolerability, and immunogenicity of an inactivated SARS-CoV-2 vaccine (CoronaVac) in healthy adults aged 60 years and older: a randomised, double-blind, placebo-controlled, phase 1/2 clinical trial** Zhiwei Wu, Yaling Hu, Miao Xu, Zhen Chen, Wanqi Yang, Zhiwei Jiang, Minjie Li, Hui Jin, Guoliang Cui, Panpan Chen, … Weidong Yin *The Lancet Infectious Diseases* (2021-06) <https://doi.org/fx8z> DOI: [10.1016/s1473-3099(20)30987-7](https://doi.org/10.1016/s1473-3099(20)30987-7) · PMID: [33548194](https://www.ncbi.nlm.nih.gov/pubmed/33548194) · PMCID: [PMC7906628](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7906628)

67. **Development of an inactivated vaccine candidate for SARS-CoV-2** Qiang Gao, Linlin Bao, Haiyan Mao, Lin Wang, Kangwei Xu, Minnan Yang, Yajing Li, Ling Zhu, Nan Wang, Zhe Lv, … Chuan Qin *Science* (2020-07-03) <https://doi.org/ggvckc> DOI: [10.1126/science.abc1932](https://doi.org/10.1126/science.abc1932) · PMID: [32376603](https://www.ncbi.nlm.nih.gov/pubmed/32376603) · PMCID: [PMC7202686](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7202686)

68. **Safety, tolerability, and immunogenicity of an inactivated SARS-CoV-2 vaccine in healthy adults aged 18–59 years: a randomised, double-blind, placebo-controlled, phase 1/2 clinical trial** Yanjun Zhang, Gang Zeng, Hongxing Pan, Changgui Li, Yaling Hu, Kai Chu, Weixiao Han, Zhen Chen, Rong Tang, Weidong Yin, … Fengcai Zhu *The Lancet Infectious Diseases* (2021-02) <https://doi.org/fpcx> DOI: [10.1016/s1473-3099(20)30843-4](https://doi.org/10.1016/s1473-3099(20)30843-4) · PMID: [33217362](https://www.ncbi.nlm.nih.gov/pubmed/33217362) · PMCID: [PMC7832443](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7832443)

69. **Background document on the inactivated vaccine Sinovac-CoronaVac against COVID-19** <https://www.who.int/publications-detail-redirect/WHO-2019-nCoV-vaccines-SAGE_recommendation-Sinovac-CoronaVac-background-2021.1>

70. **Efficacy and safety of an inactivated whole-virion SARS-CoV-2 vaccine (CoronaVac): interim results of a double-blind, randomised, placebo-controlled, phase 3 trial in Turkey** Mine Durusu Tanriover, Hamdi Levent Doğanay, Murat Akova, Hatice Rahmet Güner, Alpay Azap, Sıla Akhan, Şükran Köse, Fatma Şebnem Erdinç, Emin Halis Akalın, Ömer Fehmi Tabak, … Kurtuluş Aksu *The Lancet* (2021-07) <https://doi.org/gk898z> DOI: [10.1016/s0140-6736(21)01429-x](https://doi.org/10.1016/s0140-6736(21)01429-x) · PMID: [34246358](https://www.ncbi.nlm.nih.gov/pubmed/34246358) · PMCID: [PMC8266301](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8266301)

71. **Interim report: Safety and immunogenicity of an inactivated vaccine against SARS-CoV-2 in healthy chilean adults in a phase 3 clinical trial** Susan M Bueno, Katia Abarca, Pablo A González, Nicolás MS Gálvez, Jorge A Soto, Luisa F Duarte, Bárbara M Schultz, Gaspar A Pacheco, Liliana A González, Yaneisi Vázquez, … Alexis M Kalergis *Cold Spring Harbor Laboratory* (2021-04-01) <https://doi.org/gmwn42> DOI: [10.1101/2021.03.31.21254494](https://doi.org/10.1101/2021.03.31.21254494)

72. **Coronavirus Vaccine Tracker** Carl Zimmer, Jonathan Corum, Sui-Lee Wee, Matthew Kristoffersen *The New York Times* (2020-06-10) <https://www.nytimes.com/interactive/2020/science/coronavirus-vaccine-tracker.html>

73. **SARS-CoV-2 vaccines strategies: a comprehensive review of phase 3 candidates** Nikolaos C Kyriakidis, Andrés López-Cortés, Eduardo Vásconez González, Alejandra Barreto Grimaldos, Esteban Ortiz Prado *npj Vaccines* (2021-02-22) <https://doi.org/gjsgc4> DOI: [10.1038/s41541-021-00292-w](https://doi.org/10.1038/s41541-021-00292-w) · PMID: [33619260](https://www.ncbi.nlm.nih.gov/pubmed/33619260) · PMCID: [PMC7900244](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7900244)

74. **Development of an Inactivated Vaccine Candidate, BBIBP-CorV, with Potent Protection against SARS-CoV-2** Hui Wang, Yuntao Zhang, Baoying Huang, Wei Deng, Yaru Quan, Wenling Wang, Wenbo Xu, Yuxiu Zhao, Na Li, Jin Zhang, … Xiaoming Yang *Cell* (2020-08) <https://doi.org/ghms9s> DOI: [10.1016/j.cell.2020.06.008](https://doi.org/10.1016/j.cell.2020.06.008) · PMID: [32778225](https://www.ncbi.nlm.nih.gov/pubmed/32778225) · PMCID: [PMC7275151](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7275151)

75. **Effect of an Inactivated Vaccine Against SARS-CoV-2 on Safety and Immunogenicity Outcomes** Shengli Xia, Kai Duan, Yuntao Zhang, Dongyang Zhao, Huajun Zhang, Zhiqiang Xie, Xinguo Li, Cheng Peng, Yanbo Zhang, Wei Zhang, … Xiaoming Yang *JAMA* (2020-09-08) <https://doi.org/gg72mg> DOI: [10.1001/jama.2020.15543](https://doi.org/10.1001/jama.2020.15543) · PMID: [32789505](https://www.ncbi.nlm.nih.gov/pubmed/32789505) · PMCID: [PMC7426884](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7426884)

76. **Immunogenicity and protective efficacy of BBV152: a whole virion inactivated SARS CoV-2 vaccine in the Syrian hamster model** Sreelekshmy Mohandas, Pragya D Yadav, Anita Shete, Priya Abraham, Krishna Mohan, Gajanan Sapkal, Chandrashekhar Mote, Dimpal Nyayanit, Nivedita Gupta, VK Srini, … Balram Bhargava *Research Square Platform LLC* (2020-09-16) <https://doi.org/gmwn5d> DOI: [10.21203/rs.3.rs-76768/v1](https://doi.org/10.21203/rs.3.rs-76768/v1)

77. **Immunogenicity and protective efficacy of inactivated SARS-CoV-2 vaccine candidate, BBV152 in rhesus macaques** Pragya D Yadav, Raches Ella, Sanjay Kumar, Dilip R Patil, Sreelekshmy Mohandas, Anita M Shete, Krishna M Vadrevu, Gaurav Bhati, Gajanan Sapkal, Himanshu Kaushal, … Balram Bhargava *Nature Communications* (2021-03-02) <https://doi.org/gmwn4c> DOI: [10.1038/s41467-021-21639-w](https://doi.org/10.1038/s41467-021-21639-w) · PMID: [33654090](https://www.ncbi.nlm.nih.gov/pubmed/33654090) · PMCID: [PMC7925524](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7925524)

78. **Safety and immunogenicity of an inactivated SARS-CoV-2 vaccine, BBV152: a double-blind, randomised, phase 1 trial** Raches Ella, Krishna Mohan Vadrevu, Harsh Jogdand, Sai Prasad, Siddharth Reddy, Vamshi Sarangi, Brunda Ganneru, Gajanan Sapkal, Pragya Yadav, Priya Abraham, … Balram Bhargava *The Lancet Infectious Diseases* (2021-05) <https://doi.org/gkrthh> DOI: [10.1016/s1473-3099(20)30942-7](https://doi.org/10.1016/s1473-3099(20)30942-7) · PMID: [33485468](https://www.ncbi.nlm.nih.gov/pubmed/33485468) · PMCID: [PMC7825810](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7825810)

79. **Safety and immunogenicity of an inactivated SARS-CoV-2 vaccine, BBV152: interim results from a double-blind, randomised, multicentre, phase 2 trial, and 3-month follow-up of a double-blind, randomised phase 1 trial** Raches Ella, Siddharth Reddy, Harsh Jogdand, Vamshi Sarangi, Brunda Ganneru, Sai Prasad, Dipankar Das, Dugyala Raju, Usha Praturi, Gajanan Sapkal, … Krishna Mohan Vadrevu *The Lancet Infectious Diseases* (2021-07) <https://doi.org/gh7597> DOI: [10.1016/s1473-3099(21)00070-0](https://doi.org/10.1016/s1473-3099(21)00070-0) · PMID: [33705727](https://www.ncbi.nlm.nih.gov/pubmed/33705727) · PMCID: [PMC8221739](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8221739)

80. **Bharat Biotech: Covaxin – COVID19 Vaccine Tracker** <https://covid19.trackvaccines.org/vaccines/9/>

81. **Safety and immunogenicity of an inactivated SARS-CoV-2 vaccine, BBIBP-CorV: a randomised, double-blind, placebo-controlled, phase 1/2 trial** Shengli Xia, Yuntao Zhang, Yanxia Wang, Hui Wang, Yunkai Yang, George Fu Gao, Wenjie Tan, Guizhen Wu, Miao Xu, Zhiyong Lou, … Xiaoming Yang *The Lancet Infectious Diseases* (2021-01) <https://doi.org/ghjkrf> DOI: [10.1016/s1473-3099(20)30831-8](https://doi.org/10.1016/s1473-3099(20)30831-8) · PMID: [33069281](https://www.ncbi.nlm.nih.gov/pubmed/33069281) · PMCID: [PMC7561304](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7561304)

82. **How the Sinovac Vaccine Works** Jonathan Corum, Carl Zimmer *The New York Times* (2020-12-24) <https://www.nytimes.com/interactive/2020/health/sinovac-covid-19-vaccine.html>

83. **Officials Stress That the Pandemic ‘Is Not Over Yet’ as U.S. Vaccinations Begin** Karen Zraick *The New York Times* (2020-12-16) <https://www.nytimes.com/live/2020/12/16/world/covid-19-coronavirus>

84. **Ensayo Clínico de Fase III, Aleatorio, Doble Ciego y Controlado Con Placebo Paralelo, Para Evaluar la Seguridad y la Eficacia Protectora de la Vacuna Inactivada Contra el SARS-CoV-2 en la Población Sana de 18 años o más, en Perú** Universidad Peruana Cayetano Heredia *clinicaltrials.gov* (2021-04-27) <https://clinicaltrials.gov/ct2/show/NCT04612972>

85. **Effect of 2 Inactivated SARS-CoV-2 Vaccines on Symptomatic COVID-19 Infection in Adults** Nawal Al Kaabi, Yuntao Zhang, Shengli Xia, Yunkai Yang, Manaf M Al Qahtani, Najiba Abdulrazzaq, Majed Al Nusair, Mohamed Hassany, Jaleela S Jawad, Jehad Abdalla, … Xiaoming Yang *JAMA* (2021-05-26) <https://doi.org/gj7khd> DOI: [10.1001/jama.2021.8565](https://doi.org/10.1001/jama.2021.8565) · PMID: [34037666](https://www.ncbi.nlm.nih.gov/pubmed/34037666) · PMCID: [PMC8156175](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8156175)

86. **Efficacy, safety, and lot to lot immunogenicity of an inactivated SARS-CoV-2 vaccine (BBV152): a, double-blind, randomised, controlled phase 3 trial** Raches Ella, Siddarth Reddy, William Blackwelder, Varsha Potdar, Pragya Yadav, Vamshi Sarangi, Vinay Kumar Aileni, Suman Kanungo, Sanjay Rai, Prabhakar Reddy, … *Cold Spring Harbor Laboratory* (2021-07-02) <https://doi.org/gmns9m> DOI: [10.1101/2021.06.30.21259439](https://doi.org/10.1101/2021.06.30.21259439)

87. **Sinopharm's COVID-19 vaccine 79% effective, seeks approval in China** Reuters (2020-12-30) <https://www.reuters.com/article/health-coronavirus-china-vaccine-int-idUSKBN2940CA>

88. **Brazil institute says CoronaVac efficacy above 50%, but delays full results** Reuters (2020-12-23) <https://www.reuters.com/article/us-health-coronavirus-sinovac-brazil-idUSKBN28X2CR>

89. **Turkey and Brazil Say Chinese Vaccine Effective, With Sparse Supporting Data** Carl Zimmer, Ernesto Londoño *The New York Times* (2020-12-25) <https://www.nytimes.com/2020/12/25/health/turkey-brazil-sinovac-coronavirus-vaccine.html>

90. **Effectiveness of an Inactivated SARS-CoV-2 Vaccine in Chile** Alejandro Jara, Eduardo A Undurraga, Cecilia González, Fabio Paredes, Tomás Fontecilla, Gonzalo Jara, Alejandra Pizarro, Johanna Acevedo, Katherinne Leo, Francisco Leon, … Rafael Araos *New England Journal of Medicine* (2021-09-02) <https://doi.org/gk475w> DOI: [10.1056/nejmoa2107715](https://doi.org/10.1056/nejmoa2107715) · PMID: [34233097](https://www.ncbi.nlm.nih.gov/pubmed/34233097) · PMCID: [PMC8279092](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8279092)

91. **Susceptibility of Circulating SARS-CoV-2 Variants to Neutralization** Guo-Lin Wang, Zhuang-Ye Wang, Li-Jun Duan, Qing-Chuan Meng, Ming-Dong Jiang, Jing Cao, Lin Yao, Ka-Li Zhu, Wu-Chun Cao, Mai-Juan Ma *New England Journal of Medicine* (2021-06-17) <https://doi.org/gjnrhz> DOI: [10.1056/nejmc2103022](https://doi.org/10.1056/nejmc2103022) · PMID: [33822491](https://www.ncbi.nlm.nih.gov/pubmed/33822491) · PMCID: [PMC8063885](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8063885)

92. **Comparable neutralization of SARS-CoV-2 Delta AY.1 and Delta in individuals sera vaccinated with BBV152** Pragya D Yadav, Rima R Sahay, Gajanan Sapkal, Dimpal Nyayanit, Anita M Shete, Gururaj Deshpande, Deepak Y Patil, Nivedita Gupta, Sanjay Kumar, Priya Abraham, … Balram Bhargava *Cold Spring Harbor Laboratory* (2021-08-01) <https://doi.org/gmx72g> DOI: [10.1101/2021.07.30.454511](https://doi.org/10.1101/2021.07.30.454511)

93. **Neutralization of Beta and Delta variant with sera of COVID-19 recovered cases and vaccinees of inactivated COVID-19 vaccine BBV152/Covaxin** Pragya D Yadav, Gajanan N Sapkal, Raches Ella, Rima R Sahay, Dimpal A Nyayanit, Deepak Y Patil, Gururaj Deshpande, Anita M Shete, Nivedita Gupta, VKrishna Mohan, … Balram Bhargava *Journal of Travel Medicine* (2021-07-06) <https://doi.org/gmwn4x> DOI: [10.1093/jtm/taab104](https://doi.org/10.1093/jtm/taab104) · PMID: [34230972](https://www.ncbi.nlm.nih.gov/pubmed/34230972) · PMCID: [PMC8344909](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8344909)

94. **Inactivated COVID-19 vaccine BBV152/COVAXIN effectively neutralizes recently emerged B.1.1.7 variant of SARS-CoV-2** Gajanan N Sapkal, Pragya D Yadav, Raches Ella, Gururaj R Deshpande, Rima R Sahay, Nivedita Gupta, Krishna Mohan Vadrevu, Priya Abraham, Samiran Panda, Balram Bhargava *Journal of Travel Medicine* (2021-03-27) <https://doi.org/gjs7m8> DOI: [10.1093/jtm/taab051](https://doi.org/10.1093/jtm/taab051) · PMID: [33772577](https://www.ncbi.nlm.nih.gov/pubmed/33772577) · PMCID: [PMC8083765](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8083765)

95. **Neutralization of SARS-CoV-2 VOC 501Y.V2 by human antisera elicited by both inactivated BBIBP-CorV and recombinant dimeric RBD ZF2001 vaccines** Baoying Huang, Lianpan Dai, Hui Wang, Zhongyu Hu, Xiaoming Yang, Wenjie Tan, George F Gao *Cold Spring Harbor Laboratory* (2021-02-02) <https://doi.org/gh2px7> DOI: [10.1101/2021.02.01.429069](https://doi.org/10.1101/2021.02.01.429069)

96. **Antibody and T cell responses to Sinopharm/BBIBP-CorV in naïve and previously infected individuals in Sri Lanka** Chandima Jeewandara, Inoka Sepali Aberathna, Pradeep Darshana Pushpakumara, Achala Kamaladasa, Dinuka Guruge, Deshni Jayathilaka, Banuri Gunasekara, Shyrar Tanussiya, Heshan Kuruppu, Thushali Ranasinghe, … Gathsaurie Neelika Malavige *Cold Spring Harbor Laboratory* (2021-07-19) <https://doi.org/gk86qx> DOI: [10.1101/2021.07.15.21260621](https://doi.org/10.1101/2021.07.15.21260621)

97. **They Relied on Chinese Vaccines. Now They’re Battling Outbreaks.** Sui-Lee Wee *The New York Times* (2021-06-22) <https://www.nytimes.com/2021/06/22/business/economy/china-vaccines-covid-outbreak.html>

98. **An Open-label,Phase Ⅳ Clinical Trial to Evaluate the Immunogenicity and Safety of the Inactivated SARS-CoV-2 Vaccine (Vero Cell) in Healthy Population Aged From 18 to 59 Years.** Sinovac Research and Development Co., Ltd. *clinicaltrials.gov* (2021-09-22) <https://clinicaltrials.gov/ct2/show/NCT04962308>

99. **Covaxin booster dose: What is it? What does govt say about this?** Hindustan Times (2021-07-07) <https://www.hindustantimes.com/india-news/covaxin-booster-dose-what-is-it-what-does-govt-say-about-this-101625644184446.html>

100. **A booster dose is immunogenic and will be needed for older adults who have completed two doses vaccination with CoronaVac: a randomised, double-blind, placebo-controlled, phase 1/2 clinical trial** Minjie Li, Juan Yang, Lin Wang, Qianhui Wu, Zhiwei Wu, Wen Zheng, Lei Wang, Wanying Lu, Xiaowei Deng, Cheng Peng, … Weidong Yin *Cold Spring Harbor Laboratory* (2021-08-08) <https://doi.org/grsh> DOI: [10.1101/2021.08.03.21261544](https://doi.org/10.1101/2021.08.03.21261544)

101. **Immunogenicity and safety of a third dose, and immune persistence of CoronaVac vaccine in healthy adults aged 18-59 years: interim results from a double-blind, randomized, placebo-controlled phase 2 clinical trial** Hongxing Pan, Qianhui Wu, Gang Zeng, Juan Yang, Deyu Jiang, Xiaowei Deng, Kai Chu, Wen Zheng, Fengcai Zhu, Hongjie Yu, Weidong Yin *Cold Spring Harbor Laboratory* (2021-07-25) <https://doi.org/gm2g4h> DOI: [10.1101/2021.07.23.21261026](https://doi.org/10.1101/2021.07.23.21261026)

102. **Robust induction of B cell and T cell responses by a third dose of inactivated SARS-CoV-2 vaccine** Yihao Liu, Qin Zeng, Caiguanxi Deng, Mengyuan Li, Liubing Li, Dayue Liu, Ming Liu, Xinyuan Ruan, Jie Mei, Ruohui Mo, … Haipeng Xiao *Cold Spring Harbor Laboratory* (2021-09-15) <https://doi.org/gmx72k> DOI: [10.1101/2021.09.12.21263373](https://doi.org/10.1101/2021.09.12.21263373)

103. **China approves first mixed-vaccine trial as Delta spreads** <https://medicalxpress.com/news/2021-08-china-mixed-vaccine-trial-delta.html>

104. **Reactogenicidad, Seguridad e Inmunogenicidad de Dosis de Refuerzo de Vacunas Contra SARS-CoV-2 en Chile (Estudio REFUERZO)** Rafael Araos *clinicaltrials.gov* (2021-08-04) <https://clinicaltrials.gov/ct2/show/NCT04992182>

105. **Heterologous prime-boost immunization with CoronaVac and Convidecia** Jingxin Li, Lihua Hou, Xiling Guo, Pengfei Jin, Shipo Wu, Jiahong Zhu, Hongxing Pan, Xue Wang, Zhizhou Song, Jingxuan Wan, … Fengcai Zhu *Cold Spring Harbor Laboratory* (2021-09-06) <https://doi.org/gmx72j> DOI: [10.1101/2021.09.03.21263062](https://doi.org/10.1101/2021.09.03.21263062)

106. **Vaccines, new opportunities for a new society** Rino Rappuoli, Mariagrazia Pizza, Giuseppe Del Giudice, Ennio De Gregorio *Proceedings of the National Academy of Sciences* (2014-08-18) <https://doi.org/f6fdps> DOI: [10.1073/pnas.1402981111](https://doi.org/10.1073/pnas.1402981111) · PMID: [25136130](https://www.ncbi.nlm.nih.gov/pubmed/25136130) · PMCID: [PMC4151714](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4151714)

107. **Virus-Like Particles, a Versatile Subunit Vaccine Platform** Braeden Donaldson, Farah Al-Barwani, Vivienne Young, Sarah Scullion, Vernon Ward, Sarah Young *Advances in Delivery Science and Technology* (2014-11-01) <https://doi.org/gptgmx> DOI: [10.1007/978-1-4939-1417-3\_9](https://doi.org/10.1007/978-1-4939-1417-3_9) · PMCID: [PMC7121566](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7121566)

108. **Recombinant protein vaccines, a proven approach against coronavirus pandemics** Jeroen Pollet, Wen-Hsiang Chen, Ulrich Strych *Advanced Drug Delivery Reviews* (2021-03) <https://doi.org/gh7wss> DOI: [10.1016/j.addr.2021.01.001](https://doi.org/10.1016/j.addr.2021.01.001) · PMID: [33421475](https://www.ncbi.nlm.nih.gov/pubmed/33421475) · PMCID: [PMC7788321](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7788321)

109. **Virus-like particles: preparation, immunogenicity and their roles as nanovaccines and drug nanocarriers** Saghi Nooraei, Howra Bahrulolum, Zakieh Sadat Hoseini, Camellia Katalani, Abbas Hajizade, Andrew J Easton, Gholamreza Ahmadian *Journal of Nanobiotechnology* (2021-02-25) <https://doi.org/gk635z> DOI: [10.1186/s12951-021-00806-7](https://doi.org/10.1186/s12951-021-00806-7) · PMID: [33632278](https://www.ncbi.nlm.nih.gov/pubmed/33632278) · PMCID: [PMC7905985](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7905985)

110. **Vaccine Design** Michael F Powell, Mark J Newman (editors) *Pharmaceutical Biotechnology* (1995) <https://doi.org/gh3zp9> DOI: [10.1007/978-1-4615-1823-5](https://doi.org/10.1007/978-1-4615-1823-5)

111. **Virus-like particles as immunogens** Rob Noad, Polly Roy *Trends in Microbiology* (2003-09) <https://doi.org/dg35hw> DOI: [10.1016/s0966-842x(03)00208-7](https://doi.org/10.1016/s0966-842x(03)00208-7)

112. **Peptide Vaccine: Progress and Challenges** Weidang Li, Medha Joshi, Smita Singhania, Kyle Ramsey, Ashlesh Murthy *Vaccines* (2014-07-02) <https://doi.org/gcfszb> DOI: [10.3390/vaccines2030515](https://doi.org/10.3390/vaccines2030515) · PMID: [26344743](https://www.ncbi.nlm.nih.gov/pubmed/26344743) · PMCID: [PMC4494216](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4494216)

113. **Role of AS04 in human papillomavirus vaccine: mode of action and clinical profile** Nathalie Garçon, Martine Wettendorff, Marcelle Van Mechelen *Expert Opinion on Biological Therapy* (2011-04-04) <https://doi.org/bvtmpk> DOI: [10.1517/14712598.2011.573624](https://doi.org/10.1517/14712598.2011.573624) · PMID: [21457083](https://www.ncbi.nlm.nih.gov/pubmed/21457083)

114. **Vaccine adjuvants: Understanding the structure and mechanism of adjuvanticity** Shuting Shi, Haoru Zhu, Xinyu Xia, Zhihui Liang, Xuehu Ma, Bingbing Sun *Vaccine* (2019-05) <https://doi.org/gk6vqb> DOI: [10.1016/j.vaccine.2019.04.055](https://doi.org/10.1016/j.vaccine.2019.04.055) · PMID: [31047671](https://www.ncbi.nlm.nih.gov/pubmed/31047671)

115. **Immunogenicity of a receptor-binding domain of SARS coronavirus spike protein in mice: Implications for a subunit vaccine** Alexander N Zakhartchouk, Chetna Sharon, Malathy Satkunarajah, Thierry Auperin, Sathiyanarayanan Viswanathan, George Mutwiri, Martin Petric, Raymond H See, Robert C Brunham, BBrett Finlay, … Lorne A Babiuk *Vaccine* (2007-01) <https://doi.org/b92cpk> DOI: [10.1016/j.vaccine.2006.06.084](https://doi.org/10.1016/j.vaccine.2006.06.084) · PMID: [16919855](https://www.ncbi.nlm.nih.gov/pubmed/16919855) · PMCID: [PMC7115608](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7115608)

116. **Receptor-binding domain of SARS-CoV spike protein induces long-term protective immunity in an animal model** Lanying Du, Guangyu Zhao, Yuxian He, Yan Guo, Bo-Jian Zheng, Shibo Jiang, Yusen Zhou *Vaccine* (2007-04) <https://doi.org/drpspr> DOI: [10.1016/j.vaccine.2006.10.031](https://doi.org/10.1016/j.vaccine.2006.10.031) · PMID: [17092615](https://www.ncbi.nlm.nih.gov/pubmed/17092615) · PMCID: [PMC7115660](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7115660)

117. **A 219-mer CHO-Expressing Receptor-Binding Domain of SARS-CoV S Protein Induces Potent Immune Responses and Protective Immunity** Lanying Du, Guangyu Zhao, Chris CS Chan, Lin Li, Yuxian He, Yusen Zhou, Bo-Jian Zheng, Shibo Jiang *Viral Immunology* (2010-04) <https://doi.org/b5ghkz> DOI: [10.1089/vim.2009.0090](https://doi.org/10.1089/vim.2009.0090) · PMID: [20374001](https://www.ncbi.nlm.nih.gov/pubmed/20374001) · PMCID: [PMC2883479](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2883479)

118. **Antigenic and Immunogenic Characterization of Recombinant Baculovirus-Expressed Severe Acute Respiratory Syndrome Coronavirus Spike Protein: Implication for Vaccine Design** Yuxian He, Jingjing Li, Susanne Heck, Sara Lustigman, Shibo Jiang *Journal of Virology* (2006-06-15) <https://doi.org/bkcf55> DOI: [10.1128/jvi.00083-06](https://doi.org/10.1128/jvi.00083-06) · PMID: [16731915](https://www.ncbi.nlm.nih.gov/pubmed/16731915) · PMCID: [PMC1472569](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1472569)

119. **Immunogenicity and Protection Efficacy of Monomeric and Trimeric Recombinant SARS Coronavirus Spike Protein Subunit Vaccine Candidates** Jie Li, Laura Ulitzky, Erica Silberstein, Deborah R Taylor, Raphael Viscidi *Viral Immunology* (2013-04) <https://doi.org/f4tdd4> DOI: [10.1089/vim.2012.0076](https://doi.org/10.1089/vim.2012.0076) · PMID: [23573979](https://www.ncbi.nlm.nih.gov/pubmed/23573979) · PMCID: [PMC3624630](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3624630)

120. **Antigenicity and immunogenicity of SARS-CoV S protein receptor-binding domain stably expressed in CHO cells** Lanying Du, Guangyu Zhao, Lin Li, Yuxian He, Yusen Zhou, Bo-Jian Zheng, Shibo Jiang *Biochemical and Biophysical Research Communications* (2009-07) <https://doi.org/brx5bg> DOI: [10.1016/j.bbrc.2009.05.003](https://doi.org/10.1016/j.bbrc.2009.05.003) · PMID: [19422787](https://www.ncbi.nlm.nih.gov/pubmed/19422787) · PMCID: [PMC2750803](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2750803)

121. **Elicitation of Immunity in Mice After Immunization with the S2 Subunit of the Severe Acute Respiratory Syndrome Coronavirus** Yingjun Guo, Shuhan Sun, Kaiyu Wang, Shu Zhang, Weijia Zhu, Ze Chen *DNA and Cell Biology* (2005-08) <https://doi.org/bqrpd7> DOI: [10.1089/dna.2005.24.510](https://doi.org/10.1089/dna.2005.24.510) · PMID: [16101349](https://www.ncbi.nlm.nih.gov/pubmed/16101349)

122. **Identification of Immunodominant Epitopes on the Membrane Protein of the Severe Acute Respiratory Syndrome-Associated Coronavirus** Yuxian He, Yusen Zhou, Pamela Siddiqui, Jinkui Niu, Shibo Jiang *Journal of Clinical Microbiology* (2005-08) <https://doi.org/bn4tfg> DOI: [10.1128/jcm.43.8.3718-3726.2005](https://doi.org/10.1128/jcm.43.8.3718-3726.2005) · PMID: [16081901](https://www.ncbi.nlm.nih.gov/pubmed/16081901) · PMCID: [PMC1234014](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1234014)

123. **Boosted expression of the SARS-CoV nucleocapsid protein in tobacco and its immunogenicity in mice** Nuoyan Zheng, Ran Xia, Cuiping Yang, Bojiao Yin, Yin Li, Chengguo Duan, Liming Liang, Huishan Guo, Qi Xie *Vaccine* (2009-08) <https://doi.org/cmwbzj> DOI: [10.1016/j.vaccine.2009.05.073](https://doi.org/10.1016/j.vaccine.2009.05.073) · PMID: [19523911](https://www.ncbi.nlm.nih.gov/pubmed/19523911) · PMCID: [PMC7115566](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7115566)

124. **Immunological characterizations of the nucleocapsid protein based SARS vaccine candidates** S LIU, C LENG, S LIEN, H CHI, C HUANG, C LIN, W LIAN, C CHEN, S HSIEH, P CHONG *Vaccine* (2006-04-12) <https://doi.org/crmzqd> DOI: [10.1016/j.vaccine.2006.01.058](https://doi.org/10.1016/j.vaccine.2006.01.058) · PMID: [16494977](https://www.ncbi.nlm.nih.gov/pubmed/16494977) · PMCID: [PMC7115648](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7115648)

125. **Subunit Vaccines Against Emerging Pathogenic Human Coronaviruses** Ning Wang, Jian Shang, Shibo Jiang, Lanying Du *Frontiers in Microbiology* (2020-02-28) <https://doi.org/ggpxnq> DOI: [10.3389/fmicb.2020.00298](https://doi.org/10.3389/fmicb.2020.00298) · PMID: [32265848](https://www.ncbi.nlm.nih.gov/pubmed/32265848) · PMCID: [PMC7105881](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7105881)

126. **Yeast-expressed recombinant protein of the receptor-binding domain in SARS-CoV spike protein with deglycosylated forms as a SARS vaccine candidate** Wen-Hsiang Chen, Lanying Du, Shivali M Chag, Cuiqing Ma, Nancy Tricoche, Xinrong Tao, Christopher A Seid, Elissa M Hudspeth, Sara Lustigman, Chien-Te K Tseng, … Shibo Jiang *Human Vaccines & Immunotherapeutics* (2013-12-30) <https://doi.org/ghms54> DOI: [10.4161/hv.27464](https://doi.org/10.4161/hv.27464) · PMID: [24355931](https://www.ncbi.nlm.nih.gov/pubmed/24355931) · PMCID: [PMC4130269](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4130269)

127. **Evaluation of candidate vaccine approaches for MERS-CoV** Lingshu Wang, Wei Shi, MGordon Joyce, Kayvon Modjarrad, Yi Zhang, Kwanyee Leung, Christopher R Lees, Tongqing Zhou, Hadi M Yassine, Masaru Kanekiyo, … Barney S Graham *Nature Communications* (2015-07-28) <https://doi.org/f7mqhd> DOI: [10.1038/ncomms8712](https://doi.org/10.1038/ncomms8712) · PMID: [26218507](https://www.ncbi.nlm.nih.gov/pubmed/26218507) · PMCID: [PMC4525294](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4525294)

128. **MERS-CoV spike protein: Targets for vaccines and therapeutics** Qihui Wang, Gary Wong, Guangwen Lu, Jinghua Yan, George F Gao *Antiviral Research* (2016-09) <https://doi.org/f86fvj> DOI: [10.1016/j.antiviral.2016.07.015](https://doi.org/10.1016/j.antiviral.2016.07.015) · PMID: [27468951](https://www.ncbi.nlm.nih.gov/pubmed/27468951) · PMCID: [PMC7113765](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7113765)

129. **Recombinant Receptor Binding Domain Protein Induces Partial Protective Immunity in Rhesus Macaques Against Middle East Respiratory Syndrome Coronavirus Challenge** Jiaming Lan, Yanfeng Yao, Yao Deng, Hong Chen, Guangwen Lu, Wen Wang, Linlin Bao, Wei Deng, Qiang Wei, George F Gao, … Wenjie Tan *EBioMedicine* (2015-10) <https://doi.org/gfn5b7> DOI: [10.1016/j.ebiom.2015.08.031](https://doi.org/10.1016/j.ebiom.2015.08.031) · PMID: [26629538](https://www.ncbi.nlm.nih.gov/pubmed/26629538) · PMCID: [PMC4634622](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4634622)

130. **Tailoring Subunit Vaccine Immunity with Adjuvant Combinations and Delivery Routes Using the Middle East Respiratory Coronavirus (MERS-CoV) Receptor-Binding Domain as an Antigen** Jiaming Lan, Yao Deng, Hong Chen, Guangwen Lu, Wen Wang, Xiaojuan Guo, Zhuozhuang Lu, George F Gao, Wenjie Tan *PLoS ONE* (2014-11-18) <https://doi.org/gh4zb6> DOI: [10.1371/journal.pone.0112602](https://doi.org/10.1371/journal.pone.0112602) · PMID: [25405618](https://www.ncbi.nlm.nih.gov/pubmed/25405618) · PMCID: [PMC4236105](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4236105)

131. **Engineering a stable CHO cell line for the expression of a MERS-coronavirus vaccine antigen** Mun Peak Nyon, Lanying Du, Chien-Te Kent Tseng, Christopher A Seid, Jeroen Pollet, Kevin S Naceanceno, Anurodh Agrawal, Abdullah Algaissi, Bi-Hung Peng, Wanbo Tai, … Peter J Hotez *Vaccine* (2018-03) <https://doi.org/gdd62m> DOI: [10.1016/j.vaccine.2018.02.065](https://doi.org/10.1016/j.vaccine.2018.02.065) · PMID: [29496347](https://www.ncbi.nlm.nih.gov/pubmed/29496347) · PMCID: [PMC5860679](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5860679)

132. **A recombinant receptor-binding domain of MERS-CoV in trimeric form protects human dipeptidyl peptidase 4 (hDPP4) transgenic mice from MERS-CoV infection** Wanbo Tai, Guangyu Zhao, Shihun Sun, Yan Guo, Yufei Wang, Xinrong Tao, Chien-Te K Tseng, Fang Li, Shibo Jiang, Lanying Du, Yusen Zhou *Virology* (2016-12) <https://doi.org/f9c5sn> DOI: [10.1016/j.virol.2016.10.005](https://doi.org/10.1016/j.virol.2016.10.005) · PMID: [27750111](https://www.ncbi.nlm.nih.gov/pubmed/27750111) · PMCID: [PMC5167628](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5167628)

133. **The Amino Acids 736–761 of the MERS-CoV Spike Protein Induce Neutralizing Antibodies: Implications for the Development of Vaccines and Antiviral Agents** Yang Yang, Yao Deng, Bo Wen, Huijuan Wang, Xin Meng, Jiaming Lan, George F Gao, Wenjie Tan *Viral Immunology* (2014-12) <https://doi.org/f6rjbb> DOI: [10.1089/vim.2014.0080](https://doi.org/10.1089/vim.2014.0080) · PMID: [25387086](https://www.ncbi.nlm.nih.gov/pubmed/25387086) · PMCID: [PMC4259179](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4259179)

134. **The recombinant N-terminal domain of spike proteins is a potential vaccine against Middle East respiratory syndrome coronavirus (MERS-CoV) infection** Lan Jiaming, Yao Yanfeng, Deng Yao, Hu Yawei, Bao Linlin, Huang Baoying, Yan Jinghua, George F Gao, Qin Chuan, Tan Wenjie *Vaccine* (2017-01) <https://doi.org/f9htwb> DOI: [10.1016/j.vaccine.2016.11.064](https://doi.org/10.1016/j.vaccine.2016.11.064) · PMID: [27899228](https://www.ncbi.nlm.nih.gov/pubmed/27899228) · PMCID: [PMC7115548](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7115548)

135. **Vaccines based on virus-like nano-particles for use against Middle East Respiratory Syndrome (MERS) coronavirus** Alireza Hashemzadeh, Amir Avan, Gordon A Ferns, Majid Khazaei *Vaccine* (2020-08) <https://doi.org/gg4rkj> DOI: [10.1016/j.vaccine.2020.07.003](https://doi.org/10.1016/j.vaccine.2020.07.003) · PMID: [32684497](https://www.ncbi.nlm.nih.gov/pubmed/32684497) · PMCID: [PMC7837099](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7837099)

136. **Purified coronavirus spike protein nanoparticles induce coronavirus neutralizing antibodies in mice** Christopher M Coleman, Ye V Liu, Haiyan Mu, Justin K Taylor, Michael Massare, David C Flyer, Gregory M Glenn, Gale E Smith, Matthew B Frieman *Vaccine* (2014-05) <https://doi.org/f2rn4w> DOI: [10.1016/j.vaccine.2014.04.016](https://doi.org/10.1016/j.vaccine.2014.04.016) · PMID: [24736006](https://www.ncbi.nlm.nih.gov/pubmed/24736006) · PMCID: [PMC4058772](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4058772)

137. **MERS-CoV virus-like particles produced in insect cells induce specific humoural and cellular imminity in rhesus macaques** Chong Wang, Xuexing Zheng, Weiwei Gai, Yongkun Zhao, Hualei Wang, Haijun Wang, Na Feng, Hang Chi, Boning Qiu, Nan Li, … Xianzhu Xia *Oncotarget* (2016-03-30) <https://doi.org/f92z2j> DOI: [10.18632/oncotarget.8475](https://doi.org/10.18632/oncotarget.8475) · PMID: [27050368](https://www.ncbi.nlm.nih.gov/pubmed/27050368) · PMCID: [PMC5355045](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5355045)

138. **Significant Spike-Specific IgG and Neutralizing Antibodies in Mice Induced by a Novel Chimeric Virus-Like Particle Vaccine Candidate for Middle East Respiratory Syndrome Coronavirus** Jiaming Lan, Yao Deng, Jingdong Song, Baoying Huang, Wenling Wang, Wenjie Tan *Virologica Sinica* (2018-10) <https://doi.org/gpmnq7> DOI: [10.1007/s12250-018-0064-8](https://doi.org/10.1007/s12250-018-0064-8) · PMID: [30374826](https://www.ncbi.nlm.nih.gov/pubmed/30374826) · PMCID: [PMC6235757](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6235757)

139. **Coronavirus vaccine development: from SARS and MERS to COVID-19** Yen-Der Li, Wei-Yu Chi, Jun-Han Su, Louise Ferrall, Chien-Fu Hung, T-C Wu *Journal of Biomedical Science* (2020-12) <https://doi.org/gmf6bk> DOI: [10.1186/s12929-020-00695-2](https://doi.org/10.1186/s12929-020-00695-2) · PMID: [33341119](https://www.ncbi.nlm.nih.gov/pubmed/33341119) · PMCID: [PMC7749790](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7749790)

140. **Production of recombinant subunit vaccines: protein immunogens, live delivery systems and nucleic acid vaccines** Sissela Liljeqvist, Stefan Ståhl *Journal of Biotechnology* (1999-07) <https://doi.org/d4g86c> DOI: [10.1016/s0168-1656(99)00107-8](https://doi.org/10.1016/s0168-1656(99)00107-8)

141. **Acellular Pertussis Vaccines and Pertussis Resurgence: Revise or Replace?** Clara Maria Ausiello, Antonio Cassone *mBio* (2014-07) <https://doi.org/ggj6mm> DOI: [10.1128/mbio.01339-14](https://doi.org/10.1128/mbio.01339-14) · PMID: [24917600](https://www.ncbi.nlm.nih.gov/pubmed/24917600) · PMCID: [PMC4056554](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4056554)

142. **Pertussis: Challenges Today and for the Future** James D Cherry *PLoS Pathogens* (2013-07-25) <https://doi.org/gg74fv> DOI: [10.1371/journal.ppat.1003418](https://doi.org/10.1371/journal.ppat.1003418) · PMID: [23935481](https://www.ncbi.nlm.nih.gov/pubmed/23935481) · PMCID: [PMC3723573](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3723573)

143. **Advancements in the development of subunit influenza vaccines** Naru Zhang, Bo-Jian Zheng, Lu Lu, Yusen Zhou, Shibo Jiang, Lanying Du *Microbes and Infection* (2015-02) <https://doi.org/gngp52> DOI: [10.1016/j.micinf.2014.12.006](https://doi.org/10.1016/j.micinf.2014.12.006) · PMID: [25529753](https://www.ncbi.nlm.nih.gov/pubmed/25529753) · PMCID: [PMC4336774](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4336774)

144. **Vaccines – COVID19 Vaccine Tracker** <https://covid19.trackvaccines.org/vaccines/>

145. **Recent advances in the production of recombinant subunit vaccines inPichia pastoris** Man Wang, Shuai Jiang, Yefu Wang *Bioengineered* (2016-04-08) <https://doi.org/ghqkt8> DOI: [10.1080/21655979.2016.1191707](https://doi.org/10.1080/21655979.2016.1191707) · PMID: [27246656](https://www.ncbi.nlm.nih.gov/pubmed/27246656) · PMCID: [PMC4927204](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4927204)

146. **Coronavirus Pandemic (COVID-19)** Hannah Ritchie, Edouard Mathieu, Lucas Rodés-Guirao, Cameron Appel, Charlie Giattino, Esteban Ortiz-Ospina, Joe Hasell, Bobbie Macdonald, Diana Beltekian, Max Roser *Our World in Data* (2020-03-05) <https://ourworldindata.org/covid-vaccinations>

147. **SARS-CoV-2 spike glycoprotein vaccine candidate NVX-CoV2373 immunogenicity in baboons and protection in mice** Jing-Hui Tian, Nita Patel, Robert Haupt, Haixia Zhou, Stuart Weston, Holly Hammond, James Logue, Alyse D Portnoff, James Norton, Mimi Guebre-Xabier, … Gale Smith *Nature Communications* (2021-01-14) <https://doi.org/gjh782> DOI: [10.1038/s41467-020-20653-8](https://doi.org/10.1038/s41467-020-20653-8) · PMID: [33446655](https://www.ncbi.nlm.nih.gov/pubmed/33446655) · PMCID: [PMC7809486](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7809486)

148. **The Coming Age of Insect Cells for Manufacturing and Development of Protein Therapeutics** Christine M Yee, Andrew J Zak, Brett D Hill, Fei Wen *Industrial & Engineering Chemistry Research* (2018-07-09) <https://doi.org/gd332h> DOI: [10.1021/acs.iecr.8b00985](https://doi.org/10.1021/acs.iecr.8b00985) · PMID: [30886455](https://www.ncbi.nlm.nih.gov/pubmed/30886455) · PMCID: [PMC6420222](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6420222)

149. **Phase 1–2 Trial of a SARS-CoV-2 Recombinant Spike Protein Nanoparticle Vaccine** Cheryl Keech, Gary Albert, Iksung Cho, Andreana Robertson, Patricia Reed, Susan Neal, Joyce S Plested, Mingzhu Zhu, Shane Cloney-Clark, Haixia Zhou, … Gregory M Glenn *New England Journal of Medicine* (2020-12-10) <https://doi.org/gg9q7d> DOI: [10.1056/nejmoa2026920](https://doi.org/10.1056/nejmoa2026920) · PMID: [32877576](https://www.ncbi.nlm.nih.gov/pubmed/32877576) · PMCID: [PMC7494251](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7494251)

150. **Safety and Efficacy of NVX-CoV2373 Covid-19 Vaccine** Paul T Heath, Eva P Galiza, David N Baxter, Marta Boffito, Duncan Browne, Fiona Burns, David R Chadwick, Rebecca Clark, Catherine Cosgrove, James Galloway, … Seth Toback *New England Journal of Medicine* (2021-09-23) <https://doi.org/gk3zvz> DOI: [10.1056/nejmoa2107659](https://doi.org/10.1056/nejmoa2107659) · PMID: [34192426](https://www.ncbi.nlm.nih.gov/pubmed/34192426) · PMCID: [PMC8262625](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8262625)

151. **Novavax COVID-19 vaccine Nuvaxovid approved by MHRA** GOV.UK <https://www.gov.uk/government/news/novavax-covid-19-vaccine-nuvaxovid-approved-by-mhra>

152. **EMA recommends Nuvaxovid for authorisation in the EU** EMA *European Medicines Agency* (2021-12-20) <https://www.ema.europa.eu/en/news/ema-recommends-nuvaxovid-authorisation-eu>

153. **Novavax Submits Request to the U.S. FDA for Emergency Use Authorization of COVID-19 Vaccine** Novavax Investor Relations <https://ir.novavax.com/2022-01-31-Novavax-Submits-Request-to-the-U-S-FDA-for-Emergency-Use-Authorization-of-COVID-19-Vaccine>

154. **‘They rushed the process’: Vaccine maker’s woes hamper global inoculation campaign** POLITICO <https://www.politico.com/news/2021/10/19/novavax-vaccine-rush-process-global-campaign-516298>

155. **Efficacy and Safety of NVX-CoV2373 in Adults in the United States and Mexico** Lisa M Dunkle, Karen L Kotloff, Cynthia L Gay, Germán Áñez, Jeffrey M Adelglass, Alejandro Q Barrat Hernández, Wayne L Harper, Daniel M Duncanson, Monica A McArthur, Diana F Florescu, … *Cold Spring Harbor Laboratory* (2021-10-10) <https://doi.org/g5w9> DOI: [10.1101/2021.10.05.21264567](https://doi.org/10.1101/2021.10.05.21264567)

156. **Novavax Statement on UK and Mexico Phase 3 Clinical Trial Participants Considered Fully Vaccinated in the US** Novavax Investor Relations <https://ir.novavax.com/Novavax-Statement-on-UK-and-Mexico-Phase-3-Clinical-Trial-Participants-Considered-Fully-Vaccinated-in-the-US>

157. **Efficacy of NVX-CoV2373 Covid-19 Vaccine against the B.1.351 Variant** Vivek Shinde, Sutika Bhikha, Zaheer Hoosain, Moherndran Archary, Qasim Bhorat, Lee Fairlie, Umesh Lalloo, Mduduzi SL Masilela, Dhayendre Moodley, Sherika Hanley, … Shabir A Madhi *New England Journal of Medicine* (2021-05-20) <https://doi.org/gjzcxc> DOI: [10.1056/nejmoa2103055](https://doi.org/10.1056/nejmoa2103055) · PMID: [33951374](https://www.ncbi.nlm.nih.gov/pubmed/33951374) · PMCID: [PMC8091623](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8091623)

158. **Towards Vaccine 3.0: new era opened in vaccine research and industry** Joon Haeng Rhee *Clinical and Experimental Vaccine Research* (2014) <https://doi.org/gmqmg4> DOI: [10.7774/cevr.2014.3.1.1](https://doi.org/10.7774/cevr.2014.3.1.1) · PMID: [24427757](https://www.ncbi.nlm.nih.gov/pubmed/24427757) · PMCID: [PMC3890443](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3890443)

159. **Developing vaccines in the era of genomics: a decade of reverse vaccinology** KL Seib, X Zhao, R Rappuoli *Clinical Microbiology and Infection* (2012-10) <https://doi.org/gkbn9x> DOI: [10.1111/j.1469-0691.2012.03939.x](https://doi.org/10.1111/j.1469-0691.2012.03939.x) · PMID: [22882709](https://www.ncbi.nlm.nih.gov/pubmed/22882709)

160. **A Comparison of Plasmid DNA and mRNA as Vaccine Technologies** Liu *Vaccines* (2019-04-24) <https://doi.org/ggwd7r> DOI: [10.3390/vaccines7020037](https://doi.org/10.3390/vaccines7020037) · PMID: [31022829](https://www.ncbi.nlm.nih.gov/pubmed/31022829) · PMCID: [PMC6631684](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6631684)

161. **New Vaccine Technologies** Ronald W Ellis *JAMA: The Journal of the American Medical Association* (1994-03-23) <https://doi.org/b8gn86> DOI: [10.1001/jama.1994.03510360055036](https://doi.org/10.1001/jama.1994.03510360055036)

162. **DNA vaccines: a review** MA Liu *Journal of Internal Medicine* (2003-04) <https://doi.org/c9z766> DOI: [10.1046/j.1365-2796.2003.01140.x](https://doi.org/10.1046/j.1365-2796.2003.01140.x) · PMID: [12653868](https://www.ncbi.nlm.nih.gov/pubmed/12653868)

163. **Plasmid DNA vaccines: where are we now?** F Ghaffarifar *Drugs of Today* (2018) <https://doi.org/gdsqgg> DOI: [10.1358/dot.2018.54.5.2807864](https://doi.org/10.1358/dot.2018.54.5.2807864) · PMID: [29911696](https://www.ncbi.nlm.nih.gov/pubmed/29911696)

164. **Recent innovations in mRNA vaccines** Jeffrey B Ulmer, Andrew J Geall *Current Opinion in Immunology* (2016-08) <https://doi.org/f82bgg> DOI: [10.1016/j.coi.2016.05.008](https://doi.org/10.1016/j.coi.2016.05.008) · PMID: [27240054](https://www.ncbi.nlm.nih.gov/pubmed/27240054)

165. **DNA Vaccines—How Far From Clinical Use?** Dominika Hobernik, Matthias Bros *International Journal of Molecular Sciences* (2018-11-15) <https://doi.org/gmqmg3> DOI: [10.3390/ijms19113605](https://doi.org/10.3390/ijms19113605) · PMID: [30445702](https://www.ncbi.nlm.nih.gov/pubmed/30445702) · PMCID: [PMC6274812](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6274812)

166. **Engineered Nanodelivery Systems to Improve DNA Vaccine Technologies** Michael Lim, Abu Zayed Md Badruddoza, Jannatul Firdous, Mohammad Azad, Adnan Mannan, Taslim Ahmed Al-Hilal, Chong-Su Cho, Mohammad Ariful Islam *Pharmaceutics* (2020-01-01) <https://doi.org/ghwmkd> DOI: [10.3390/pharmaceutics12010030](https://doi.org/10.3390/pharmaceutics12010030) · PMID: [31906277](https://www.ncbi.nlm.nih.gov/pubmed/31906277) · PMCID: [PMC7022884](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7022884)

167. **DNA** <https://www.who.int/teams/health-product-and-policy-standards/standards-and-specifications/vaccines-quality/dna>

168. **Safety, Tolerability and Immunogenicity of INO-4800 for COVID-19 in Healthy Volunteers - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04336410>

169. **Electroporation delivery of DNA vaccines: prospects for success** Niranjan Y Sardesai, David B Weiner *Current Opinion in Immunology* (2011-06) <https://doi.org/cq8b4p> DOI: [10.1016/j.coi.2011.03.008](https://doi.org/10.1016/j.coi.2011.03.008) · PMID: [21530212](https://www.ncbi.nlm.nih.gov/pubmed/21530212) · PMCID: [PMC3109217](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3109217)

170. **Tolerability of intramuscular and intradermal delivery by CELLECTRA <sup>®</sup> adaptive constant current electroporation device in healthy volunteers** Malissa C Diehl, Jessica C Lee, Stephen E Daniels, Pablo Tebas, Amir S Khan, Mary Giffear, Niranjan Y Sardesai, Mark L Bagarazzi *Human Vaccines & Immunotherapeutics* (2014-10-27) <https://doi.org/ggrj7h> DOI: [10.4161/hv.24702](https://doi.org/10.4161/hv.24702) · PMID: [24051434](https://www.ncbi.nlm.nih.gov/pubmed/24051434) · PMCID: [PMC3906411](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3906411)

171. **Multivalent and Multipathogen Viral Vector Vaccines** Katharina B Lauer, Ray Borrow, Thomas J Blanchard *Clinical and Vaccine Immunology* (2017-01) <https://doi.org/f9tsw2> DOI: [10.1128/cvi.00298-16](https://doi.org/10.1128/cvi.00298-16) · PMID: [27535837](https://www.ncbi.nlm.nih.gov/pubmed/27535837) · PMCID: [PMC5216423](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5216423)

172. **Viral vectors as vaccine platforms: from immunogenicity to impact** Katie J Ewer, Teresa Lambe, Christine S Rollier, Alexandra J Spencer, Adrian VS Hill, Lucy Dorrell *Current Opinion in Immunology* (2016-08) <https://doi.org/f82tb6> DOI: [10.1016/j.coi.2016.05.014](https://doi.org/10.1016/j.coi.2016.05.014) · PMID: [27286566](https://www.ncbi.nlm.nih.gov/pubmed/27286566)

173. **Clinical Assessment of a Novel Recombinant Simian Adenovirus ChAdOx1 as a Vectored Vaccine Expressing Conserved Influenza A Antigens** Richard D Antrobus, Lynda Coughlan, Tamara K Berthoud, Matthew D Dicks, Adrian VS Hill, Teresa Lambe, Sarah C Gilbert *Molecular Therapy* (2014-03) <https://doi.org/f5vhv3> DOI: [10.1038/mt.2013.284](https://doi.org/10.1038/mt.2013.284) · PMID: [24374965](https://www.ncbi.nlm.nih.gov/pubmed/24374965) · PMCID: [PMC3944330](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3944330)

174. **Vaccine Candidates against Coronavirus Infections. Where Does COVID-19 Stand?** Jawad Al-Kassmy, Jannie Pedersen, Gary Kobinger *Viruses* (2020-08-07) <https://doi.org/ghsfmc> DOI: [10.3390/v12080861](https://doi.org/10.3390/v12080861) · PMID: [32784685](https://www.ncbi.nlm.nih.gov/pubmed/32784685) · PMCID: [PMC7472384](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7472384)

175. **Poxviruses as vaccine vectors** P-P Pastoret, A Vanderplasschen *Comparative Immunology, Microbiology and Infectious Diseases* (2003-10) <https://doi.org/cnw6vw> DOI: [10.1016/s0147-9571(03)00019-5](https://doi.org/10.1016/s0147-9571(03)00019-5)

176. **Enhancing poxvirus vectors vaccine immunogenicity** Juan García-Arriaza, Mariano Esteban *Human Vaccines & Immunotherapeutics* (2014-05-05) <https://doi.org/ghz9tw> DOI: [10.4161/hv.28974](https://doi.org/10.4161/hv.28974) · PMID: [25424927](https://www.ncbi.nlm.nih.gov/pubmed/25424927) · PMCID: [PMC4896794](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4896794)

177. **New Insights on Adenovirus as Vaccine Vectors** Marcio O Lasaro, Hildegund CJ Ertl *Molecular Therapy* (2009-08) <https://doi.org/dcz549> DOI: [10.1038/mt.2009.130](https://doi.org/10.1038/mt.2009.130) · PMID: [19513019](https://www.ncbi.nlm.nih.gov/pubmed/19513019) · PMCID: [PMC2835230](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2835230)

178. **Attenuated vesicular stomatitis viruses as vaccine vectors.** A Roberts, L Buonocore, R Price, J Forman, JK Rose *Journal of virology* (1999-05) <https://www.ncbi.nlm.nih.gov/pubmed/10196265> DOI: [10.1128/jvi.73.5.3723-3732.1999](https://doi.org/10.1128/jvi.73.5.3723-3732.1999) · PMID: [10196265](https://www.ncbi.nlm.nih.gov/pubmed/10196265) · PMCID: [PMC104148](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC104148)

179. **Vesicular stomatitis virus: re-inventing the bullet** Brian D Lichty, Anthony T Power, David F Stojdl, John C Bell *Trends in Molecular Medicine* (2004-05) <https://doi.org/fg6wv5> DOI: [10.1016/j.molmed.2004.03.003](https://doi.org/10.1016/j.molmed.2004.03.003) · PMID: [15121047](https://www.ncbi.nlm.nih.gov/pubmed/15121047)

180. **Viral vectors as vaccine platforms: deployment in sight** Christine S Rollier, Arturo Reyes-Sandoval, Matthew G Cottingham, Katie Ewer, Adrian VS Hill *Current Opinion in Immunology* (2011-06) <https://doi.org/d8p72q> DOI: [10.1016/j.coi.2011.03.006](https://doi.org/10.1016/j.coi.2011.03.006) · PMID: [21514130](https://www.ncbi.nlm.nih.gov/pubmed/21514130)

181. **Progress and prospects: immune responses to viral vectors** S Nayak, RW Herzog *Gene Therapy* (2009-11-12) <https://doi.org/ctbtwq> DOI: [10.1038/gt.2009.148](https://doi.org/10.1038/gt.2009.148) · PMID: [19907498](https://www.ncbi.nlm.nih.gov/pubmed/19907498) · PMCID: [PMC3044498](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3044498)

182. **Developments in Viral Vector-Based Vaccines** Takehiro Ura, Kenji Okuda, Masaru Shimada *Vaccines* (2014-07-29) <https://doi.org/gcfnx9> DOI: [10.3390/vaccines2030624](https://doi.org/10.3390/vaccines2030624) · PMID: [26344749](https://www.ncbi.nlm.nih.gov/pubmed/26344749) · PMCID: [PMC4494222](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4494222)

183. **Development and Applications of Viral Vectored Vaccines to Combat Zoonotic and Emerging Public Health Threats** Sophia M Vrba, Natalie M Kirk, Morgan E Brisse, Yuying Liang, Hinh Ly *Vaccines* (2020-11-13) <https://doi.org/gh23ww> DOI: [10.3390/vaccines8040680](https://doi.org/10.3390/vaccines8040680) · PMID: [33202961](https://www.ncbi.nlm.nih.gov/pubmed/33202961) · PMCID: [PMC7712223](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7712223)

184. **A Vaccine against Ebola Virus** Erica Ollmann Saphire *Cell* (2020-04) <https://doi.org/gprj4w> DOI: [10.1016/j.cell.2020.03.011](https://doi.org/10.1016/j.cell.2020.03.011) · PMID: [32243796](https://www.ncbi.nlm.nih.gov/pubmed/32243796)

185. **Viral Vector Malaria Vaccines Induce High-Level T Cell and Antibody Responses in West African Children and Infants** Carly M Bliss, Abdoulie Drammeh, Georgina Bowyer, Guillaume S Sanou, Ya Jankey Jagne, Oumarou Ouedraogo, Nick J Edwards, Casimir Tarama, Nicolas Ouedraogo, Mireille Ouedraogo, … Katie J Ewer *Molecular Therapy* (2017-02) <https://doi.org/f9xwv3> DOI: [10.1016/j.ymthe.2016.11.003](https://doi.org/10.1016/j.ymthe.2016.11.003) · PMID: [28153101](https://www.ncbi.nlm.nih.gov/pubmed/28153101) · PMCID: [PMC5368405](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5368405)

186. **Viral vectors for malaria vaccine development** Shengqiang Li, Emily Locke, Joseph Bruder, David Clarke, Denise L Doolan, Menzo JE Havenga, Adrian VS Hill, Peter Liljestrom, Thomas P Monath, Hussein Y Naim, … Filip Dubovsky *Vaccine* (2007-03) <https://doi.org/fh9fn6> DOI: [10.1016/j.vaccine.2006.07.035](https://doi.org/10.1016/j.vaccine.2006.07.035) · PMID: [16914237](https://www.ncbi.nlm.nih.gov/pubmed/16914237) · PMCID: [PMC7131149](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7131149)

187. **Chimpanzee Adenovirus Vector Ebola Vaccine** Julie E Ledgerwood, Adam D DeZure, Daphne A Stanley, Emily E Coates, Laura Novik, Mary E Enama, Nina M Berkowitz, Zonghui Hu, Gyan Joshi, Aurélie Ploquin, … Barney S Graham *New England Journal of Medicine* (2017-03-09) <https://doi.org/xdr> DOI: [10.1056/nejmoa1410863](https://doi.org/10.1056/nejmoa1410863) · PMID: [25426834](https://www.ncbi.nlm.nih.gov/pubmed/25426834)

188. **Recombinant Vesicular Stomatitis Virus–Based Vaccines Against Ebola and Marburg Virus Infections** Thomas W Geisbert, Heinz Feldmann *The Journal of Infectious Diseases* (2011-11) <https://doi.org/fcvgxq> DOI: [10.1093/infdis/jir349](https://doi.org/10.1093/infdis/jir349) · PMID: [21987744](https://www.ncbi.nlm.nih.gov/pubmed/21987744) · PMCID: [PMC3218670](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3218670)

189. **Ebola virus vaccines: an overview of current approaches** Andrea Marzi, Heinz Feldmann *Expert Review of Vaccines* (2014-02-27) <https://doi.org/f52bn6> DOI: [10.1586/14760584.2014.885841](https://doi.org/10.1586/14760584.2014.885841) · PMID: [24575870](https://www.ncbi.nlm.nih.gov/pubmed/24575870) · PMCID: [PMC4785864](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4785864)

190. **Development of replication-competent viral vectors for HIV vaccine delivery** Christopher L Parks, Louis J Picker, CRichter King *Current Opinion in HIV and AIDS* (2013-09) <https://doi.org/f5b5qm> DOI: [10.1097/coh.0b013e328363d389](https://doi.org/10.1097/coh.0b013e328363d389) · PMID: [23925000](https://www.ncbi.nlm.nih.gov/pubmed/23925000) · PMCID: [PMC4040527](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4040527)

191. **Different HIV pox viral vector-based vaccines and adjuvants can induce unique antigen presenting cells that modulate CD8 T cell avidity** Shubhanshi Trivedi, Ronald J Jackson, Charani Ranasinghe *Virology* (2014-11) <https://doi.org/f6ngrk> DOI: [10.1016/j.virol.2014.09.004](https://doi.org/10.1016/j.virol.2014.09.004) · PMID: [25261870](https://www.ncbi.nlm.nih.gov/pubmed/25261870)

192. **Comparative evaluation of two severe acute respiratory syndrome (SARS) vaccine candidates in mice challenged with SARS coronavirus** Raymond H See, Alexander N Zakhartchouk, Martin Petric, David J Lawrence, Catherine PY Mok, Robert J Hogan, Thomas Rowe, Lois A Zitzow, Karuna P Karunakaran, Mary M Hitt, … BBrett Finlay *Journal of General Virology* (2006-03-01) <https://doi.org/fm9v5c> DOI: [10.1099/vir.0.81579-0](https://doi.org/10.1099/vir.0.81579-0) · PMID: [16476986](https://www.ncbi.nlm.nih.gov/pubmed/16476986)

193. **Severe acute respiratory syndrome vaccine efficacy in ferrets: whole killed virus and adenovirus-vectored vaccines** Raymond H See, Martin Petric, David J Lawrence, Catherine PY Mok, Thomas Rowe, Lois A Zitzow, Karuna P Karunakaran, Thomas G Voss, Robert C Brunham, Jack Gauldie, … Rachel L Roper *Journal of General Virology* (2008-09-01) <https://doi.org/c5wc6w> DOI: [10.1099/vir.0.2008/001891-0](https://doi.org/10.1099/vir.0.2008/001891-0) · PMID: [18753223](https://www.ncbi.nlm.nih.gov/pubmed/18753223)

194. **Update with the development of Ebola vaccines and implications of emerging evidence to inform future policy recommendations** Hoi Ting Yeung *World Health Organization SAGE meeting background* (2018-09-19) <https://www.who.int/immunization/sage/meetings/2018/october/2_Ebola_SAGE2018Oct_BgDoc_20180919.pdf>

195. **ChAdOx1 and MVA based vaccine candidates against MERS-CoV elicit neutralising antibodies and cellular immune responses in mice** Naif Khalaf Alharbi, Eriko Padron-Regalado, Craig P Thompson, Alexandra Kupke, Daniel Wells, Megan A Sloan, Keith Grehan, Nigel Temperton, Teresa Lambe, George Warimwe, … Sarah C Gilbert *Vaccine* (2017-06) <https://doi.org/gbms8z> DOI: [10.1016/j.vaccine.2017.05.032](https://doi.org/10.1016/j.vaccine.2017.05.032) · PMID: [28579232](https://www.ncbi.nlm.nih.gov/pubmed/28579232) · PMCID: [PMC5516308](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5516308)

196. **A single dose of ChAdOx1 MERS provides protective immunity in rhesus macaques** Neeltje van Doremalen, Elaine Haddock, Friederike Feldmann, Kimberly Meade-White, Trenton Bushmaker, Robert J Fischer, Atsushi Okumura, Patrick W Hanley, Greg Saturday, Nick J Edwards, … Vincent J Munster *Science Advances* (2020-06-12) <https://doi.org/gjkthv> DOI: [10.1126/sciadv.aba8399](https://doi.org/10.1126/sciadv.aba8399) · PMID: [32577525](https://www.ncbi.nlm.nih.gov/pubmed/32577525) · PMCID: [PMC7286676](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7286676)

197. **Safety and immunogenicity of a candidate Middle East respiratory syndrome coronavirus viral-vectored vaccine: a dose-escalation, open-label, non-randomised, uncontrolled, phase 1 trial** Pedro M Folegatti, Mustapha Bittaye, Amy Flaxman, Fernando Ramos Lopez, Duncan Bellamy, Alexandra Kupke, Catherine Mair, Rebecca Makinson, Jonathan Sheridan, Cornelius Rohde, … Sarah Gilbert *The Lancet Infectious Diseases* (2020-07) <https://doi.org/ggtxgp> DOI: [10.1016/s1473-3099(20)30160-2](https://doi.org/10.1016/s1473-3099(20)30160-2) · PMID: [32325038](https://www.ncbi.nlm.nih.gov/pubmed/32325038) · PMCID: [PMC7172901](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7172901)

198. **ChAdOx1 nCoV-19 vaccine prevents SARS-CoV-2 pneumonia in rhesus macaques** Neeltje van Doremalen, Teresa Lambe, Alexandra Spencer, Sandra Belij-Rammerstorfer, Jyothi N Purushotham, Julia R Port, Victoria A Avanzato, Trenton Bushmaker, Amy Flaxman, Marta Ulaszewska, … Vincent J Munster *Nature* (2020-07-30) <https://doi.org/gg67jr> DOI: [10.1038/s41586-020-2608-y](https://doi.org/10.1038/s41586-020-2608-y) · PMID: [32731258](https://www.ncbi.nlm.nih.gov/pubmed/32731258) · PMCID: [PMC8436420](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8436420)

199. **Safety and immunogenicity of the ChAdOx1 nCoV-19 vaccine against SARS-CoV-2: a preliminary report of a phase 1/2, single-blind, randomised controlled trial** Pedro M Folegatti, Katie J Ewer, Parvinder K Aley, Brian Angus, Stephan Becker, Sandra Belij-Rammerstorfer, Duncan Bellamy, Sagida Bibi, Mustapha Bittaye, Elizabeth A Clutterbuck, … Yasmine Yau *The Lancet* (2020-08) <https://doi.org/gg5gwk> DOI: [10.1016/s0140-6736(20)31604-4](https://doi.org/10.1016/s0140-6736(20)31604-4) · PMID: [32702298](https://www.ncbi.nlm.nih.gov/pubmed/32702298) · PMCID: [PMC7445431](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7445431)

200. **The Russian vaccine for COVID-19** Talha Khan Burki *The Lancet Respiratory Medicine* (2020-11) <https://doi.org/ft7j> DOI: [10.1016/s2213-2600(20)30402-1](https://doi.org/10.1016/s2213-2600(20)30402-1) · PMID: [32896274](https://www.ncbi.nlm.nih.gov/pubmed/32896274) · PMCID: [PMC7837053](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7837053)

201. **Operation Warp Speed: Accelerated COVID-19 Vaccine Development Status and Efforts to Address Manufacturing Challenges** USGovernment Accountability Office <https://www.gao.gov/products/gao-21-319>

202. **Johnson & Johnson Announces a Lead Vaccine Candidate for COVID-19; Landmark New Partnership with U.S. Department of Health & Human Services; and Commitment to Supply One Billion Vaccines Worldwide for Emergency Pandemic Use | Johnson & Johnson** Content Lab U.S. <https://www.jnj.com/johnson-johnson-announces-a-lead-vaccine-candidate-for-covid-19-landmark-new-partnership-with-u-s-department-of-health-human-services-and-commitment-to-supply-one-billion-vaccines-worldwide-for-emergency-pandemic-use>

203. **Interim Results of a Phase 1–2a Trial of Ad26.COV2.S Covid-19 Vaccine** Jerald Sadoff, Mathieu Le Gars, Georgi Shukarev, Dirk Heerwegh, Carla Truyers, Anne M de Groot, Jeroen Stoop, Sarah Tete, Wim Van Damme, Isabel Leroux-Roels, … Hanneke Schuitemaker *New England Journal of Medicine* (2021-05-13) <https://doi.org/fqnt> DOI: [10.1056/nejmoa2034201](https://doi.org/10.1056/nejmoa2034201) · PMID: [33440088](https://www.ncbi.nlm.nih.gov/pubmed/33440088) · PMCID: [PMC7821985](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7821985)

204. **Single-shot Ad26 vaccine protects against SARS-CoV-2 in rhesus macaques** Noe B Mercado, Roland Zahn, Frank Wegmann, Carolin Loos, Abishek Chandrashekar, Jingyou Yu, Jinyan Liu, Lauren Peter, Katherine McMahan, Lisa H Tostanoski, … Dan H Barouch *Nature* (2020-07-30) <https://doi.org/d5d4> DOI: [10.1038/s41586-020-2607-z](https://doi.org/10.1038/s41586-020-2607-z) · PMID: [32731257](https://www.ncbi.nlm.nih.gov/pubmed/32731257) · PMCID: [PMC7581548](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7581548)

205. **Ad26 vaccine protects against SARS-CoV-2 severe clinical disease in hamsters** Lisa H Tostanoski, Frank Wegmann, Amanda J Martinot, Carolin Loos, Katherine McMahan, Noe B Mercado, Jingyou Yu, Chi N Chan, Stephen Bondoc, Carly E Starke, … Dan H Barouch *Nature Medicine* (2020-09-03) <https://doi.org/gjhgd2> DOI: [10.1038/s41591-020-1070-6](https://doi.org/10.1038/s41591-020-1070-6) · PMID: [32884153](https://www.ncbi.nlm.nih.gov/pubmed/32884153) · PMCID: [PMC7671939](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7671939)

206. **Immunogenicity and protective efficacy of one- and two-dose regimens of the Ad26.COV2.S COVID-19 vaccine candidate in adult and aged rhesus macaques** Laura Solforosi, Harmjan Kuipers, Sietske KRosendahl Huber, Joan EM van der Lubbe, Liesbeth Dekking, Dominika N Czapska-Casey, Ana Izquierdo Gil, Miranda RM Baert, Joke Drijver, Joost Vaneman, … Roland C Zahn *Cold Spring Harbor Laboratory* (2020-11-17) <https://doi.org/ghwzk9> DOI: [10.1101/2020.11.17.368258](https://doi.org/10.1101/2020.11.17.368258)

207. **SARS-CoV-2 binding and neutralizing antibody levels after vaccination with Ad26.COV2.S predict durable protection in rhesus macaques** Ramon Roozendaal, Laura Solforosi, Daniel Stieh, Jan Serroyen, Roel Straetemans, Frank Wegmann, Sietske K Rosendahl Huber, Joan EM van der Lubbe, Jenny Hendriks, Mathieu le Gars, … Roland Zahn *Cold Spring Harbor Laboratory* (2021-01-30) <https://doi.org/gjhgd4> DOI: [10.1101/2021.01.30.428921](https://doi.org/10.1101/2021.01.30.428921)

208. **Safety and efficacy of an rAd26 and rAd5 vector-based heterologous prime-boost COVID-19 vaccine: an interim analysis of a randomised controlled phase 3 trial in Russia** Denis Y Logunov, Inna V Dolzhikova, Dmitry V Shcheblyakov, Amir I Tukhvatulin, Olga V Zubkova, Alina S Dzharullaeva, Anna V Kovyrshina, Nadezhda L Lubenets, Daria M Grousova, Alina S Erokhova, … Alexander L Gintsburg *The Lancet* (2021-02) <https://doi.org/ghxj4g> DOI: [10.1016/s0140-6736(21)00234-8](https://doi.org/10.1016/s0140-6736(21)00234-8) · PMID: [33545094](https://www.ncbi.nlm.nih.gov/pubmed/33545094) · PMCID: [PMC7852454](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7852454)

209. **Janssen Investigational COVID-19 Vaccine: Interim Analysis of Phase 3 Clinical Data Released** National Institutes of Health (NIH) (2021-01-29) <https://www.nih.gov/news-events/news-releases/janssen-investigational-covid-19-vaccine-interim-analysis-phase-3-clinical-data-released>

210. **Johnson & Johnson Announces Single-Shot Janssen COVID-19 Vaccine Candidate Met Primary Endpoints in Interim Analysis of its Phase 3 ENSEMBLE Trial** Janssen (2021-01-29) <https://www.janssen.com/emea/sites/www_janssen_com_emea/files/johnson_johnson_announces_single-shot_janssen_covid-19_vaccine_candidate_met_primary_endpoints_in_interim_analysis_of_its_phase_3_ensemble_trial.pdf>

211. **AstraZeneca’s COVID-19 vaccine authorised for emergency supply in the UK** <https://www.astrazeneca.com/media-centre/press-releases/2020/astrazenecas-covid-19-vaccine-authorised-in-uk.html>

212. **The Brussels Times** <https://www.brusselstimes.com/news-contents/world/149039/1-5-million-people-have-received-sputnik-v-vaccine-russia-says-russian-direct-investment-fund-mikhail-murashko>

213. **Hungary becomes first EU country to deploy Russia's COVID-19 vaccine** Michael Daventry *euronews* (2021-02-12) <https://www.euronews.com/2021/02/12/hungary-to-begin-using-russia-s-sputnik-v-vaccine-today>

214. **San Marino buys Russia's Sputnik V after EU vaccine delivery delays** euronews (2021-02-24) <https://www.euronews.com/2021/02/24/san-marino-buys-russia-s-sputnik-v-after-eu-vaccine-delivery-delays>

215. **Belarus Starts Coronavirus Vaccination With Sputnik V** AFP *The Moscow Times* (2020-12-29) <https://www.themoscowtimes.com/2020/12/29/belarus-starts-coronavirus-vaccination-with-sputnik-v-a72512>

216. **Russia's coronavirus vaccine is alluring for Eastern Europe, creating a headache for the EU** Holly Ellyatt *CNBC* (2021-03-02) <https://www.cnbc.com/2021/03/02/russias-sputnik-vaccine-is-luring-eastern-europe-worrying-the-eu.html>

217. **B.1.351 report** <https://cov-lineages.org/global_report_B.1.351.html>

218. **Three decades of messenger RNA vaccine development** Rein Verbeke, Ine Lentacker, Stefaan C De Smedt, Heleen Dewitte *Nano Today* (2019-10) <https://doi.org/ghm43s> DOI: [10.1016/j.nantod.2019.100766](https://doi.org/10.1016/j.nantod.2019.100766)

219. **Developing mRNA-vaccine technologies** Thomas Schlake, Andreas Thess, Mariola Fotin-Mleczek, Karl-Josef Kallen *RNA Biology* (2012-11) <https://doi.org/f4qzdb> DOI: [10.4161/rna.22269](https://doi.org/10.4161/rna.22269) · PMID: [23064118](https://www.ncbi.nlm.nih.gov/pubmed/23064118) · PMCID: [PMC3597572](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3597572)

220. **mRNA vaccines — a new era in vaccinology** Norbert Pardi, Michael J Hogan, Frederick W Porter, Drew Weissman *Nature Reviews Drug Discovery* (2018-01-12) <https://doi.org/gcsmgr> DOI: [10.1038/nrd.2017.243](https://doi.org/10.1038/nrd.2017.243) · PMID: [29326426](https://www.ncbi.nlm.nih.gov/pubmed/29326426) · PMCID: [PMC5906799](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5906799)

221. **Induction of virus-specific cytotoxic T lymphocytesin vivo by liposome-entrapped mRNA** Frédéric Martinon, Sivadasan Krishnan, Gerlinde Lenzen, Rémy Magné, Elisabeth Gomard, Jean-Gérard Guillet, Jean-Paul Lévy, Pierre Meulien *European Journal of Immunology* (1993-07) <https://doi.org/b6jb3z> DOI: [10.1002/eji.1830230749](https://doi.org/10.1002/eji.1830230749) · PMID: [8325342](https://www.ncbi.nlm.nih.gov/pubmed/8325342)

222. **mRNA vaccine delivery using lipid nanoparticles** Andreas M Reichmuth, Matthias A Oberli, Ana Jaklenec, Robert Langer, Daniel Blankschtein *Therapeutic Delivery* (2016-05) <https://doi.org/f8xfzc> DOI: [10.4155/tde-2016-0006](https://doi.org/10.4155/tde-2016-0006) · PMID: [27075952](https://www.ncbi.nlm.nih.gov/pubmed/27075952) · PMCID: [PMC5439223](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5439223)

223. **Mechanism of action of mRNA-based vaccines** Carlo Iavarone, Derek T O’hagan, Dong Yu, Nicolas F Delahaye, Jeffrey B Ulmer *Expert Review of Vaccines* (2017-07-28) <https://doi.org/ggsnm6> DOI: [10.1080/14760584.2017.1355245](https://doi.org/10.1080/14760584.2017.1355245) · PMID: [28701102](https://www.ncbi.nlm.nih.gov/pubmed/28701102)

224. **RNA vaccines: an introduction** PHG Foundation <https://www.phgfoundation.org/briefing/rna-vaccines>

225. **T Follicular Helper Cell Differentiation, Function, and Roles in Disease** Shane Crotty *Immunity* (2014-10) <https://doi.org/ggsp64> DOI: [10.1016/j.immuni.2014.10.004](https://doi.org/10.1016/j.immuni.2014.10.004) · PMID: [25367570](https://www.ncbi.nlm.nih.gov/pubmed/25367570) · PMCID: [PMC4223692](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4223692)

226. **SARS-CoV-2 Vaccines: Status Report** Fatima Amanat, Florian Krammer *Immunity* (2020-04) <https://doi.org/ggrdj4> DOI: [10.1016/j.immuni.2020.03.007](https://doi.org/10.1016/j.immuni.2020.03.007) · PMID: [32259480](https://www.ncbi.nlm.nih.gov/pubmed/32259480) · PMCID: [PMC7136867](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7136867)

227. **Study in Healthy Adults to Evaluate Gene Activation After Vaccination With GlaxoSmithKline (GSK) Biologicals' Candidate Tuberculosis (TB) Vaccine GSK 692342 - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT01669096>

228. **Nucleoside-modified mRNA immunization elicits influenza virus hemagglutinin stalk-specific antibodies** Norbert Pardi, Kaela Parkhouse, Ericka Kirkpatrick, Meagan McMahon, Seth J Zost, Barbara L Mui, Ying K Tam, Katalin Karikó, Christopher J Barbosa, Thomas D Madden, … Drew Weissman *Nature Communications* (2018-08-22) <https://doi.org/gd49qt> DOI: [10.1038/s41467-018-05482-0](https://doi.org/10.1038/s41467-018-05482-0) · PMID: [30135514](https://www.ncbi.nlm.nih.gov/pubmed/30135514) · PMCID: [PMC6105651](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6105651)

229. **Cell specific delivery of modified mRNA expressing therapeutic proteins to leukocytes** Nuphar Veiga, Meir Goldsmith, Yasmin Granot, Daniel Rosenblum, Niels Dammes, Ranit Kedmi, Srinivas Ramishetti, Dan Peer *Nature Communications* (2018-10-29) <https://doi.org/gfmcrt> DOI: [10.1038/s41467-018-06936-1](https://doi.org/10.1038/s41467-018-06936-1) · PMID: [30374059](https://www.ncbi.nlm.nih.gov/pubmed/30374059) · PMCID: [PMC6206083](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6206083)

230. **Managing intellectual property to develop medicines for the world's poorest** Sylvie Fonteilles-Drabek, David Reddy, Timothy NC Wells *Nature Reviews Drug Discovery* (2017-02-24) <https://doi.org/gmqmgv> DOI: [10.1038/nrd.2017.24](https://doi.org/10.1038/nrd.2017.24) · PMID: [28232725](https://www.ncbi.nlm.nih.gov/pubmed/28232725)

231. **Immunology of COVID-19: Current State of the Science** Nicolas Vabret, Graham J Britton, Conor Gruber, Samarth Hegde, Joel Kim, Maria Kuksin, Rachel Levantovsky, Louise Malle, Alvaro Moreira, Matthew D Park, … Uri Laserson *Immunity* (2020-06) <https://doi.org/ggt54g> DOI: [10.1016/j.immuni.2020.05.002](https://doi.org/10.1016/j.immuni.2020.05.002) · PMID: [32505227](https://www.ncbi.nlm.nih.gov/pubmed/32505227) · PMCID: [PMC7200337](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7200337)

232. **Synthetic Chemically Modified mRNA (modRNA): Toward a New Technology Platform for Cardiovascular Biology and Medicine** KR Chien, L Zangi, KO Lui *Cold Spring Harbor Perspectives in Medicine* (2014-10-09) <https://doi.org/f3pvsr> DOI: [10.1101/cshperspect.a014035](https://doi.org/10.1101/cshperspect.a014035) · PMID: [25301935](https://www.ncbi.nlm.nih.gov/pubmed/25301935) · PMCID: [PMC4292072](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4292072)

233. **Pfizer and BioNTech Announce Early Positive Data from an Ongoing Phase 1/2 study of mRNA-based Vaccine Candidate Against SARS-CoV-2 | Pfizer** <https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-announce-early-positive-data-ongoing-0>

234. **Phase I, Open-Label, Dose-Ranging Study of the Safety and Immunogenicity of 2019-nCoV Vaccine (mRNA-1273) in Healthy Adults** National Institute of Allergy and Infectious Diseases (NIAID) *clinicaltrials.gov* (2020-12-17) <https://clinicaltrials.gov/ct2/show/NCT04283461>

235. **Safety and Efficacy of the BNT162b2 mRNA Covid-19 Vaccine** Fernando P Polack, Stephen J Thomas, Nicholas Kitchin, Judith Absalon, Alejandra Gurtman, Stephen Lockhart, John L Perez, Gonzalo Pérez Marc, Edson D Moreira, Cristiano Zerbini, … William C Gruber *New England Journal of Medicine* (2020-12-31) <https://doi.org/ghn625> DOI: [10.1056/nejmoa2034577](https://doi.org/10.1056/nejmoa2034577) · PMID: [33301246](https://www.ncbi.nlm.nih.gov/pubmed/33301246) · PMCID: [PMC7745181](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7745181)

236. **Efficacy and Safety of the mRNA-1273 SARS-CoV-2 Vaccine** Lindsey R Baden, Hana M El Sahly, Brandon Essink, Karen Kotloff, Sharon Frey, Rick Novak, David Diemert, Stephen A Spector, Nadine Rouphael, CBuddy Creech, … Tal Zaks *New England Journal of Medicine* (2020-12-30) <https://doi.org/ghrg8m> DOI: [10.1056/nejmoa2035389](https://doi.org/10.1056/nejmoa2035389) · PMID: [33378609](https://www.ncbi.nlm.nih.gov/pubmed/33378609) · PMCID: [PMC7787219](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7787219)

237. **FDA Takes Key Action in Fight Against COVID-19 By Issuing Emergency Use Authorization for First COVID-19 Vaccine** Office of the Commissioner *FDA* (2020-12-14) <https://www.fda.gov/news-events/press-announcements/fda-takes-key-action-fight-against-covid-19-issuing-emergency-use-authorization-first-covid-19>

238. **The Advisory Committee on Immunization Practices’ Interim Recommendation for Use of Moderna COVID-19 Vaccine — United States, December 2020** Sara E Oliver *MMWR. Morbidity and Mortality Weekly Report* (2021) <https://www.cdc.gov/mmwr/volumes/69/wr/mm695152e1.htm> DOI: [10.15585/mmwr.mm695152e1](https://doi.org/10.15585/mmwr.mm695152e1)

239. **Prevention and Attenuation of Covid-19 with the BNT162b2 and mRNA-1273 Vaccines** Mark G Thompson, Jefferey L Burgess, Allison L Naleway, Harmony Tyner, Sarang K Yoon, Jennifer Meece, Lauren EW Olsho, Alberto J Caban-Martinez, Ashley L Fowlkes, Karen Lutrick, … Manjusha Gaglani *New England Journal of Medicine* (2021-07-22) <https://doi.org/gk3bzr> DOI: [10.1056/nejmoa2107058](https://doi.org/10.1056/nejmoa2107058) · PMID: [34192428](https://www.ncbi.nlm.nih.gov/pubmed/34192428) · PMCID: [PMC8262622](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8262622)

240. **Increased risk of SARS-CoV-2 reinfection associated with emergence of Omicron in South Africa** Juliet RC Pulliam, Cari van Schalkwyk, Nevashan Govender, Anne von Gottberg, Cheryl Cohen, Michelle J Groome, Jonathan Dushoff, Koleka Mlisana, Harry Moultrie *Cold Spring Harbor Laboratory* (2021-11-11) <https://doi.org/g8gj> DOI: [10.1101/2021.11.11.21266068](https://doi.org/10.1101/2021.11.11.21266068)

241. **Coronavirus Disease 2019 (COVID-19)** CDC *Centers for Disease Control and Prevention* (2020-02-11) <https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/scientific-brief-omicron-variant.html>

242. **Sensitivity of infectious SARS-CoV-2 B.1.1.7 and B.1.351 variants to neutralizing antibodies** Delphine Planas, Timothée Bruel, Ludivine Grzelak, Florence Guivel-Benhassine, Isabelle Staropoli, Françoise Porrot, Cyril Planchais, Julian Buchrieser, Maaran Michael Rajah, Elodie Bishop, … Olivier Schwartz *Nature Medicine* (2021-03-26) <https://doi.org/gjmwwr> DOI: [10.1038/s41591-021-01318-5](https://doi.org/10.1038/s41591-021-01318-5) · PMID: [33772244](https://www.ncbi.nlm.nih.gov/pubmed/33772244)

243. **Antibody resistance of SARS-CoV-2 variants B.1.351 and B.1.1.7** Pengfei Wang, Manoj S Nair, Lihong Liu, Sho Iketani, Yang Luo, Yicheng Guo, Maple Wang, Jian Yu, Baoshan Zhang, Peter D Kwong, … David D Ho *Nature* (2021-03-08) <https://doi.org/gjhdxm> DOI: [10.1038/s41586-021-03398-2](https://doi.org/10.1038/s41586-021-03398-2) · PMID: [33684923](https://www.ncbi.nlm.nih.gov/pubmed/33684923)

244. **Neutralizing Antibodies Against SARS-CoV-2 Variants After Infection and Vaccination** Venkata Viswanadh Edara, William H Hudson, Xuping Xie, Rafi Ahmed, Mehul S Suthar *JAMA* (2021-05-11) <https://doi.org/gj29vq> DOI: [10.1001/jama.2021.4388](https://doi.org/10.1001/jama.2021.4388) · PMID: [33739374](https://www.ncbi.nlm.nih.gov/pubmed/33739374) · PMCID: [PMC7980146](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7980146)

245. **Classification of Omicron (B.1.1.529): SARS-CoV-2 Variant of Concern** <https://www.who.int/news/item/26-11-2021-classification-of-omicron-(b.1.1.529)-sars-cov-2-variant-of-concern>

246. **COVID Data Tracker** CDC *Centers for Disease Control and Prevention* (2020-03-28) <https://covid.cdc.gov/covid-data-tracker>

247. **Breakthrough Infections with SARS-CoV-2 Omicron Variant Despite Booster Dose of mRNA Vaccine** Constanze Kuhlmann, Carla Konstanze Mayer, Mathilda Claassen, Tongai G Maponga, Andrew D Sutherland, Tasnim Suliman, Megan Shaw, Wolfgang Preiser *SSRN Electronic Journal* (2021) <https://doi.org/gpnbfz> DOI: [10.2139/ssrn.3981711](https://doi.org/10.2139/ssrn.3981711)

248. **Reduced neutralization of SARS-CoV-2 B.1.617 by vaccine and convalescent serum** Chang Liu, Helen M Ginn, Wanwisa Dejnirattisai, Piyada Supasa, Beibei Wang, Aekkachai Tuekprakhon, Rungtiwa Nutalai, Daming Zhou, Alexander J Mentzer, Yuguang Zhao, … Gavin R Screaton *Cell* (2021-08) <https://doi.org/gmdhvf> DOI: [10.1016/j.cell.2021.06.020](https://doi.org/10.1016/j.cell.2021.06.020) · PMID: [34242578](https://www.ncbi.nlm.nih.gov/pubmed/34242578) · PMCID: [PMC8218332](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8218332)

249. **Broadly neutralizing antibodies overcome SARS-CoV-2 Omicron antigenic shift** Elisabetta Cameroni, Christian Saliba, John E Bowen, Laura E Rosen, Katja Culap, Dora Pinto, Laura A VanBlargan, Anna De Marco, Samantha K Zepeda, Julia di Iulio, … Davide Corti *Cold Spring Harbor Laboratory* (2021-12-14) <https://doi.org/hb7x> DOI: [10.1101/2021.12.12.472269](https://doi.org/10.1101/2021.12.12.472269) · PMID: [34931194](https://www.ncbi.nlm.nih.gov/pubmed/34931194) · PMCID: [PMC8687478](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8687478)

250. **SARS-CoV-2 Omicron: evasion of potent humoral responses and resistance to clinical immunotherapeutics relative to viral variants of concern** Anupriya Aggarwal, Alberto Ospina Stella, Gregory Walker, Anouschka Akerman, Vanessa Milogiannakis, Fabienne Brilot, Supavadee Amatayakul-Chantler, Nathan Roth, Germano Coppola, Peter Schofield, … Stuart Turville *Cold Spring Harbor Laboratory* (2021-12-15) <https://doi.org/hb73> DOI: [10.1101/2021.12.14.21267772](https://doi.org/10.1101/2021.12.14.21267772)

251. **The SARS-CoV-2 B.1.1.529 Omicron virus causes attenuated infection and disease in mice and hamsters** Michael Diamond, Peter Halfmann, Tadashi Maemura, Kiyoko Iwatsuki-Horimoto, Shun Iida, Maki Kiso, Suzanne Scheaffer, Tamarand Darling, Astha Joshi, Samantha Loeber, … Viviana Simon *Research Square Platform LLC* (2021-12-29) <https://doi.org/gpnbfx> DOI: [10.21203/rs.3.rs-1211792/v1](https://doi.org/10.21203/rs.3.rs-1211792/v1) · PMID: [34981044](https://www.ncbi.nlm.nih.gov/pubmed/34981044) · PMCID: [PMC8722607](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8722607)

252. **SARS-CoV-2 Omicron-B.1.1.529 Variant leads to less severe disease than Pango B and Delta variants strains in a mouse model of severe COVID-19** Eleanor G Bentley, Adam Kirby, Parul Sharma, Anja Kipar, Daniele F Mega, Chloe Bramwell, Rebekah Penrice-Randal, Tessa Prince, Jonathan C Brown, Jie Zhou, … James P Stewart *Cold Spring Harbor Laboratory* (2021-12-28) <https://doi.org/gpnbfb> DOI: [10.1101/2021.12.26.474085](https://doi.org/10.1101/2021.12.26.474085)

253. **The omicron (B.1.1.529) SARS-CoV-2 variant of concern does not readily infect Syrian hamsters** Rana Abdelnabi, Caroline S Foo, Xin Zhang, Viktor Lemmens, Piet Maes, Bram Slechten, Joren Raymenants, Emmanuel André, Birgit Weynand, Kai Dallemier, Johan Neyts *Cold Spring Harbor Laboratory* (2021-12-26) <https://doi.org/gpnbd9> DOI: [10.1101/2021.12.24.474086](https://doi.org/10.1101/2021.12.24.474086)

254. **Reduced Pathogenicity of the SARS-CoV-2 Omicron Variant in Hamsters** Katherine McMahan, Victoria Giffin, Lisa H Tostanoski, Benjamin Chung, Mazuba Siamatu, Mehul S Suthar, Peter Halfmann, Yoshihiro Kawaoka, Cesar Piedra-Mora, Amanda J Martinot, … Dan H Barouch *Cold Spring Harbor Laboratory* (2022-01-03) <https://doi.org/gpnbfc> DOI: [10.1101/2022.01.02.474743](https://doi.org/10.1101/2022.01.02.474743)

255. **SARS-CoV-2 Omicron spike mediated immune escape and tropism shift** Bo Meng, Isabella ATM Ferreira, Adam Abdullahi, Niluka Goonawardane, Akatsuki Saito, Izumi Kimura, Daichi Yamasoba, Pehuén Perera Gerba, Saman Fatihi, Surabhi Rathore, … *Cold Spring Harbor Laboratory* (2021-12-21) <https://doi.org/gpnbd7> DOI: [10.1101/2021.12.17.473248](https://doi.org/10.1101/2021.12.17.473248)

256. **Coronavirus in the U.S.: Latest Map and Case Count** The New York Times <https://www.nytimes.com/interactive/2021/us/covid-cases.html>

257. **Analysis | Four charts that analyze how omicron’s wave compares to previous coronavirus peaks** Shelly Tan *Washington Post* <https://www.washingtonpost.com/health/interactive/2022/omicron-comparison-cases-deaths-hospitalizations/>

258. **Effectiveness of BNT162b2 Vaccine against Omicron Variant in South Africa** Shirley Collie, Jared Champion, Harry Moultrie, Linda-Gail Bekker, Glenda Gray *New England Journal of Medicine* (2022-02-03) <https://doi.org/gnxj2w> DOI: [10.1056/nejmc2119270](https://doi.org/10.1056/nejmc2119270) · PMID: [34965358](https://www.ncbi.nlm.nih.gov/pubmed/34965358) · PMCID: [PMC8757569](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8757569)

259. **A meta-analysis of Early Results to predict Vaccine efficacy against Omicron** David S Khoury, Megan Steain, James A Triccas, Alex Sigal, Miles P Davenport, Deborah Cromer *Cold Spring Harbor Laboratory* (2021-12-14) <https://doi.org/gpnbd5> DOI: [10.1101/2021.12.13.21267748](https://doi.org/10.1101/2021.12.13.21267748)

260. **Waning 2-Dose and 3-Dose Effectiveness of mRNA Vaccines Against COVID-19–Associated Emergency Department and Urgent Care Encounters and Hospitalizations Among Adults During Periods of Delta and Omicron Variant Predominance — VISION Network, 10 States, August 2021–January 2022** Jill M Ferdinands, Suchitra Rao, Brian E Dixon, Patrick K Mitchell, Malini B DeSilva, Stephanie A Irving, Ned Lewis, Karthik Natarajan, Edward Stenehjem, Shaun J Grannis, … Bruce Fireman *MMWR. Morbidity and Mortality Weekly Report* (2022-02-18) <https://doi.org/gpfrkh> DOI: [10.15585/mmwr.mm7107e2](https://doi.org/10.15585/mmwr.mm7107e2) · PMID: [35176007](https://www.ncbi.nlm.nih.gov/pubmed/35176007) · PMCID: [PMC8853475](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8853475)

261. **COVID-19 mRNA booster vaccines elicit strong protection against SARS-CoV-2 Omicron variant in patients with cancer** Cong Zeng, John P Evans, Karthik Chakravarthy, Panke Qu, Sarah Reisinger, No-Joon Song, Mark P Rubinstein, Peter G Shields, Zihai Li, Shan-Lu Liu *Cancer Cell* (2022-02) <https://doi.org/gn2gcf> DOI: [10.1016/j.ccell.2021.12.014](https://doi.org/10.1016/j.ccell.2021.12.014) · PMID: [34986328](https://www.ncbi.nlm.nih.gov/pubmed/34986328) · PMCID: [PMC8716174](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8716174)

262. **Immune correlates analysis of the mRNA-1273 COVID-19 vaccine efficacy clinical trial** Peter B Gilbert, David C Montefiori, Adrian B McDermott, Youyi Fong, David Benkeser, Weiping Deng, Honghong Zhou, Christopher R Houchens, Karen Martins, Lakshmi Jayashankar, … *Science* (2022-01-07) <https://doi.org/gpnbff> DOI: [10.1126/science.abm3425](https://doi.org/10.1126/science.abm3425) · PMID: [34812653](https://www.ncbi.nlm.nih.gov/pubmed/34812653)

263. **Towards a population-based threshold of protection for COVID-19 vaccines** David Goldblatt, Andrew Fiore-Gartland, Marina Johnson, Adam Hunt, Christopher Bengt, Dace Zavadska, Hilda Darta Snipe, Jeremy S Brown, Lesley Workman, Heather J Zar, … Donna Ambrosino *Vaccine* (2022-01) <https://doi.org/gpnbdz> DOI: [10.1016/j.vaccine.2021.12.006](https://doi.org/10.1016/j.vaccine.2021.12.006) · PMID: [34933765](https://www.ncbi.nlm.nih.gov/pubmed/34933765) · PMCID: [PMC8673730](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8673730)

264. **Evidence for antibody as a protective correlate for COVID-19 vaccines** Kristen A Earle, Donna M Ambrosino, Andrew Fiore-Gartland, David Goldblatt, Peter B Gilbert, George R Siber, Peter Dull, Stanley A Plotkin *Vaccine* (2021-07) <https://doi.org/gnr5w7> DOI: [10.1016/j.vaccine.2021.05.063](https://doi.org/10.1016/j.vaccine.2021.05.063) · PMID: [34210573](https://www.ncbi.nlm.nih.gov/pubmed/34210573) · PMCID: [PMC8142841](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8142841)

265. **Towards Internationally standardised humoral Immune Correlates of Protection from SARS-CoV-2 infection and COVID-19 disease** Javier Castillo-Olivares, David A Wells, Matteo Ferrari, Andrew Chan, Peter Smith, Angalee Nadesalingam, Minna Paloniemi, George Carnell, Luis Ohlendorf, Diego Cantoni, … Jonathan Heeney *Cold Spring Harbor Laboratory* (2021-05-23) <https://doi.org/gk7czq> DOI: [10.1101/2021.05.21.21257572](https://doi.org/10.1101/2021.05.21.21257572)

266. **A longitudinal study of SARS-CoV-2-infected patients reveals a high correlation between neutralizing antibodies and COVID-19 severity** Vincent Legros, Solène Denolly, Manon Vogrig, Bertrand Boson, Eglantine Siret, Josselin Rigaill, Sylvie Pillet, Florence Grattard, Sylvie Gonzalo, Paul Verhoeven, … Bruno Pozzetto *Cellular &amp; Molecular Immunology* (2021-01-06) <https://doi.org/gh5qjr> DOI: [10.1038/s41423-020-00588-2](https://doi.org/10.1038/s41423-020-00588-2) · PMID: [33408342](https://www.ncbi.nlm.nih.gov/pubmed/33408342) · PMCID: [PMC7786875](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7786875)

267. **4th Dose COVID mRNA Vaccines’ Immunogenicity &amp; Efficacy Against Omicron VOC** Gili Regev-Yochay, Tal Gonen, Mayan Gilboa, Michal Mandelboim, Victoria Indenbaum, Sharon Amit, Lilac Meltzer, Keren Asraf, Carmit Cohen, Ronen Fluss, … Yaniv Lustig *Cold Spring Harbor Laboratory* (2022-02-15) <https://doi.org/gpnbfd> DOI: [10.1101/2022.02.15.22270948](https://doi.org/10.1101/2022.02.15.22270948)

268. **Safety and immunogenicity of an rAd26 and rAd5 vector-based heterologous prime-boost COVID-19 vaccine in two formulations: two open, non-randomised phase 1/2 studies from Russia** Denis Y Logunov, Inna V Dolzhikova, Olga V Zubkova, Amir I Tukhvatulin, Dmitry V Shcheblyakov, Alina S Dzharullaeva, Daria M Grousova, Alina S Erokhova, Anna V Kovyrshina, Andrei G Botikov, … Alexander L Gintsburg *The Lancet* (2020-09) <https://doi.org/gg96hq> DOI: [10.1016/s0140-6736(20)31866-3](https://doi.org/10.1016/s0140-6736(20)31866-3) · PMID: [32896291](https://www.ncbi.nlm.nih.gov/pubmed/32896291) · PMCID: [PMC7471804](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7471804)

269. **WHO lists additional COVID-19 vaccine for emergency use and issues interim policy recommendations** <https://www.who.int/news/item/07-05-2021-who-lists-additional-covid-19-vaccine-for-emergency-use-and-issues-interim-policy-recommendations>

270. **Immunogenicity and safety of the CoronaVac inactivated vaccine in patients with autoimmune rheumatic diseases: a phase 4 trial** Ana C Medeiros-Ribeiro, Nadia E Aikawa, Carla GS Saad, Emily FN Yuki, Tatiana Pedrosa, Solange RG Fusco, Priscila T Rojo, Rosa MR Pereira, Samuel K Shinjo, Danieli CO Andrade, … Eloisa Bonfa *Nature Medicine* (2021-07-30) <https://doi.org/gmwn4j> DOI: [10.1038/s41591-021-01469-5](https://doi.org/10.1038/s41591-021-01469-5) · PMID: [34331051](https://www.ncbi.nlm.nih.gov/pubmed/34331051)

271. **Safety, tolerability, and immunogenicity of an inactivated SARS-CoV-2 vaccine (CoronaVac) in healthy children and adolescents: a double-blind, randomised, controlled, phase 1/2 clinical trial** Bihua Han, Yufei Song, Changgui Li, Wanqi Yang, Qingxia Ma, Zhiwei Jiang, Minjie Li, Xiaojuan Lian, Wenbin Jiao, Lei Wang, … Qiang Gao *The Lancet Infectious Diseases* (2021-12) <https://doi.org/gn93> DOI: [10.1016/s1473-3099(21)00319-4](https://doi.org/10.1016/s1473-3099(21)00319-4) · PMID: [34197764](https://www.ncbi.nlm.nih.gov/pubmed/34197764) · PMCID: [PMC8238449](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8238449)

272. **Viral dynamics in asymptomatic patients with COVID-19** Rui Zhou, Furong Li, Fengjuan Chen, Huamin Liu, Jiazhen Zheng, Chunliang Lei, Xianbo Wu *International Journal of Infectious Diseases* (2020-07) <https://doi.org/ggxs96> DOI: [10.1016/j.ijid.2020.05.030](https://doi.org/10.1016/j.ijid.2020.05.030) · PMID: [32437933](https://www.ncbi.nlm.nih.gov/pubmed/32437933) · PMCID: [PMC7211726](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7211726)

273. **Higher viral loads in asymptomatic COVID-19 patients might be the invisible part of the iceberg** Imran Hasanoglu, Gulay Korukluoglu, Dilek Asilturk, Yasemin Cosgun, Ayse Kaya Kalem, Ayşe Basak Altas, Bircan Kayaaslan, Fatma Eser, Esra Akkan Kuzucu, Rahmet Guner *Infection* (2020-11-24) <https://doi.org/ghxsp4> DOI: [10.1007/s15010-020-01548-8](https://doi.org/10.1007/s15010-020-01548-8) · PMID: [33231841](https://www.ncbi.nlm.nih.gov/pubmed/33231841) · PMCID: [PMC7685188](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7685188)

274. **Relationships between Viral Load and the Clinical Course of COVID-19** Hiroyuki Tsukagoshi, Daisuke Shinoda, Mariko Saito, Kaori Okayama, Mitsuru Sada, Hirokazu Kimura, Nobuhiro Saruki *Viruses* (2021-02-15) <https://doi.org/gndc5c> DOI: [10.3390/v13020304](https://doi.org/10.3390/v13020304) · PMID: [33672005](https://www.ncbi.nlm.nih.gov/pubmed/33672005) · PMCID: [PMC7919281](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7919281)

275. **Estimating the extent of asymptomatic COVID-19 and its potential for community transmission: Systematic review and meta-analysis** Oyungerel Byambasuren, Magnolia Cardona, Katy Bell, Justin Clark, Mary-Louise McLaws, Paul Glasziou *Official Journal of the Association of Medical Microbiology and Infectious Disease Canada* (2020-12) <https://doi.org/gh7qmm> DOI: [10.3138/jammi-2020-0030](https://doi.org/10.3138/jammi-2020-0030)

276. **SARS-CoV-2 Infection after Vaccination in Health Care Workers in California** Jocelyn Keehner, Lucy E Horton, Michael A Pfeffer, Christopher A Longhurst, Robert T Schooley, Judith S Currier, Shira R Abeles, Francesca J Torriani *New England Journal of Medicine* (2021-05-06) <https://doi.org/gjjr6h> DOI: [10.1056/nejmc2101927](https://doi.org/10.1056/nejmc2101927) · PMID: [33755376](https://www.ncbi.nlm.nih.gov/pubmed/33755376) · PMCID: [PMC8008750](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8008750)

277. **Impact of the Coronavirus Disease 2019 (COVID-19) Vaccine on Asymptomatic Infection Among Patients Undergoing Preprocedural COVID-19 Molecular Screening** Aaron J Tande, Benjamin D Pollock, Nilay D Shah, Gianrico Farrugia, Abinash Virk, Melanie Swift, Laura Breeher, Matthew Binnicker, Elie F Berbari *Clinical Infectious Diseases* (2021-03-10) <https://doi.org/gjg8qf> DOI: [10.1093/cid/ciab229](https://doi.org/10.1093/cid/ciab229) · PMID: [33704435](https://www.ncbi.nlm.nih.gov/pubmed/33704435) · PMCID: [PMC7989519](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7989519)

278. **Association Between Vaccination With BNT162b2 and Incidence of Symptomatic and Asymptomatic SARS-CoV-2 Infections Among Health Care Workers** Yoel Angel, Avishay Spitzer, Oryan Henig, Esther Saiag, Eli Sprecher, Hagit Padova, Ronen Ben-Ami *JAMA* (2021-06-22) <https://doi.org/gjwp6b> DOI: [10.1001/jama.2021.7152](https://doi.org/10.1001/jama.2021.7152) · PMID: [33956048](https://www.ncbi.nlm.nih.gov/pubmed/33956048) · PMCID: [PMC8220476](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8220476)

279. **Initial report of decreased SARS-CoV-2 viral load after inoculation with the BNT162b2 vaccine** Matan Levine-Tiefenbrun, Idan Yelin, Rachel Katz, Esma Herzel, Ziv Golan, Licita Schreiber, Tamar Wolf, Varda Nadler, Amir Ben-Tov, Jacob Kuint, … Roy Kishony *Nature Medicine* (2021-03-29) <https://doi.org/gjmx9h> DOI: [10.1038/s41591-021-01316-7](https://doi.org/10.1038/s41591-021-01316-7) · PMID: [33782619](https://www.ncbi.nlm.nih.gov/pubmed/33782619)

280. **Virological and serological kinetics of SARS-CoV-2 Delta variant vaccine-breakthrough infections: a multi-center cohort study** Po Ying Chia, Sean Wei Xiang Ong, Calvin J Chiew, Li Wei Ang, Jean-Marc Chavatte, Tze-Minn Mak, Lin Cui, Shirin Kalimuddin, Wan Ni Chia, Chee Wah Tan, … Barnaby Edward Young *Cold Spring Harbor Laboratory* (2021-07-31) <https://doi.org/gmd72x> DOI: [10.1101/2021.07.28.21261295](https://doi.org/10.1101/2021.07.28.21261295)

281. **Shedding of Infectious SARS-CoV-2 Despite Vaccination** Kasen K Riemersma, Brittany E Grogan, Amanda Kita-Yarbro, Peter J Halfmann, Hannah E Segaloff, Anna Kocharian, Kelsey R Florek, Ryan Westergaard, Allen Bateman, Gunnar E Jeppson, … Katarina M Grande *Cold Spring Harbor Laboratory* (2021-07-31) <https://doi.org/gmfh6j> DOI: [10.1101/2021.07.31.21261387](https://doi.org/10.1101/2021.07.31.21261387)

282. **No Significant Difference in Viral Load Between Vaccinated and Unvaccinated, Asymptomatic and Symptomatic Groups When Infected with SARS-CoV-2 Delta Variant** Charlotte B Acharya, John Schrom, Anthea M Mitchell, David A Coil, Carina Marquez, Susana Rojas, Chung Yu Wang, Jamin Liu, Genay Pilarowski, Leslie Solis, … Diane Havlir *Cold Spring Harbor Laboratory* (2021-09-29) <https://doi.org/gndc47> DOI: [10.1101/2021.09.28.21264262](https://doi.org/10.1101/2021.09.28.21264262)

283. **Safety, Immunogenicity, and Efficacy of a COVID-19 Vaccine (NVX-CoV2373) Co-administered With Seasonal Influenza Vaccines** Seth Toback, Eva Galiza, Catherine Cosgrove, James Galloway, Anna L Goodman, Pauline A Swift, Sankarasubramanian Rajaram, Alison Graves-Jones, Jonathan Edelman, Fiona Burns, … Paul T Heath *Cold Spring Harbor Laboratory* (2021-06-13) <https://doi.org/gngp57> DOI: [10.1101/2021.06.09.21258556](https://doi.org/10.1101/2021.06.09.21258556)

284. **Novavax Initiates Phase 1/2 Clinical Trial of Combination Vaccine for COVID-19 and Seasonal Influenza** Novavax Investor Relations <https://ir.novavax.com/2021-09-08-Novavax-Initiates-Phase-1-2-Clinical-Trial-of-Combination-Vaccine-for-COVID-19-and-Seasonal-Influenza>

285. **Combination Respiratory Vaccine Containing Recombinant SARS-CoV-2 Spike and Quadrivalent Seasonal Influenza Hemagglutinin Nanoparticles with Matrix-M Adjuvant** Michael J Massare, Nita Patel, Bin Zhou, Sonia Maciejewski, Rhonda Flores, Mimi Guebre-Xabier, Jing-Hui Tian, Alyse D Portnoff, Louis Fries, Vivek Shinde, … Gale Smith *Cold Spring Harbor Laboratory* (2021-05-05) <https://doi.org/gngp56> DOI: [10.1101/2021.05.05.442782](https://doi.org/10.1101/2021.05.05.442782)

286. **Reactogenicidad, Seguridad e Inmunogenicidad de Dosis de Refuerzo de Vacunas Contra SARS-CoV-2 en Chile (Estudio REFUERZO)** Rafael Araos *clinicaltrials.gov* (2021-08-04) <https://clinicaltrials.gov/ct2/show/NCT04992182>

287. **SARS Vaccine Development** Shibo Jiang, Yuxian He, Shuwen Liu *Emerging Infectious Diseases* (2005-07) <https://doi.org/gm2qkj> DOI: [10.3201/eid1107.050219](https://doi.org/10.3201/eid1107.050219) · PMID: [16022774](https://www.ncbi.nlm.nih.gov/pubmed/16022774) · PMCID: [PMC3371787](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3371787)

288. **A decade after SARS: strategies for controlling emerging coronaviruses** Rachel L Graham, Eric F Donaldson, Ralph S Baric *Nature Reviews Microbiology* (2013-11-11) <https://doi.org/ggwrzg> DOI: [10.1038/nrmicro3143](https://doi.org/10.1038/nrmicro3143) · PMID: [24217413](https://www.ncbi.nlm.nih.gov/pubmed/24217413) · PMCID: [PMC5147543](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5147543)

289. **Vaccines for emerging infectious diseases: Lessons from MERS coronavirus and Zika virus** Joel N Maslow *Human Vaccines & Immunotherapeutics* (2017-08-28) <https://doi.org/gk7gb4> DOI: [10.1080/21645515.2017.1358325](https://doi.org/10.1080/21645515.2017.1358325) · PMID: [28846484](https://www.ncbi.nlm.nih.gov/pubmed/28846484) · PMCID: [PMC5718785](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5718785)

290. **Ebola vaccine: Little and late** Jon Cohen *Science* (2014-09-19) <https://doi.org/gm2qkd> DOI: [10.1126/science.345.6203.1441](https://doi.org/10.1126/science.345.6203.1441) · PMID: [25237082](https://www.ncbi.nlm.nih.gov/pubmed/25237082)

291. **Clinical development of a recombinant Ebola vaccine in the midst of an unprecedented epidemic** Beth-Ann G Coller, Jeffrey Blue, Rituparna Das, Sheri Dubey, Lynn Finelli, Swati Gupta, Frans Helmond, Rebecca J Grant-Klein, Kenneth Liu, Jakub Simon, … Thomas P Monath *Vaccine* (2017-08) <https://doi.org/gbw3rt> DOI: [10.1016/j.vaccine.2017.05.097](https://doi.org/10.1016/j.vaccine.2017.05.097) · PMID: [28647166](https://www.ncbi.nlm.nih.gov/pubmed/28647166)

292. **First-in-human, Randomised, Double-blind, Placebo-controlled, Dose-escalation Study in Healthy Young Adults Evaluating the Safety and Immunogenicity of COVI-VAC, a Live Attenuated Vaccine Candidate for Prevention of COVID-19** Codagenix, Inc *clinicaltrials.gov* (2021-07-26) <https://clinicaltrials.gov/ct2/show/NCT04619628>

293. **Phase 1, Open-Label, Dose-Escalation Study to Evaluate Tolerability, Safety, and Immunogenicity of an Intranasal Live Attenuated Respiratory Syncytial Virus Vaccine Expressing Spike Protein of SARS-CoV-2 in Healthy Adults Ages 18 - 69 Years** Meissa Vaccines, Inc. *clinicaltrials.gov* (2021-07-01) <https://clinicaltrials.gov/ct2/show/NCT04798001>

294. **BCG Vaccination to Protect Healthcare Workers Against COVID-19 - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04327206>

295. **BCG Vaccine for Health Care Workers as Defense Against COVID 19 - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04348370>

296. **Safety and immunogenicity of a novel human Enterovirus 71 (EV71) vaccine: A randomized, placebo-controlled, double-blind, Phase I clinical trial** Yan-Ping Li, Zheng-Lun Liang, Qiang Gao, Li-Rong Huang, Qun-Ying Mao, Shu-Qun Wen, Yan Liu, Wei-Dong Yin, Rong-Cheng Li, Jun-Zhi Wang *Vaccine* (2012-05) <https://doi.org/gh7tjn> DOI: [10.1016/j.vaccine.2012.03.010](https://doi.org/10.1016/j.vaccine.2012.03.010) · PMID: [22426327](https://www.ncbi.nlm.nih.gov/pubmed/22426327)

297. **Double-Blind, Randomized, Placebo-Controlled Phase III Clinical Trial to Evaluate the Efficacy and Safety of treating Healthcare Professionals with the Adsorbed COVID-19 (Inactivated) Vaccine Manufactured by Sinovac – PROFISCOV: A structured summary of a study protocol for a randomised controlled trial** Ricardo Palacios, Elizabeth González Patiño, Roberta de Oliveira Piorelli, Monica Tilli Reis Pessoa Conde, Ana Paula Batista, Gang Zeng, Qianqian Xin, Esper G Kallas, Jorge Flores, Christian F Ockenhouse, Christopher Gast *Trials* (2020-10-15) <https://doi.org/ghjkrh> DOI: [10.1186/s13063-020-04775-4](https://doi.org/10.1186/s13063-020-04775-4) · PMID: [33059771](https://www.ncbi.nlm.nih.gov/pubmed/33059771) · PMCID: [PMC7558252](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7558252)

298. **Sinovac: CoronaVac – COVID19 Vaccine Tracker** <https://covid19.trackvaccines.org/vaccines/7/>

299. **Bharat Biotech Announces Phase 3 Results of COVAXIN** Bharat Biotech (2021-03-03) <https://www.bharatbiotech.com/images/press/covaxin-phase3-efficacy-results.pdf>

300. **Ocugen's COVID-19 Vaccine Co-Development Partner, Bharat Biotech shares Phase 3 Interim Results of COVAXIN, Demonstrates Efficacy of 81%** Biogenetech (2021-03-05) <https://www.biogenetech.co.th/wp-content/uploads/2021/03/5-Ocugen.pdf>

301. **Zimbabwe authorizes use of India's first indigenous COVID-19 vaccine - Xinhua | English.news.cn** <http://www.xinhuanet.com/english/2021-03/04/c_139783893.htm>

302. **Booster dose: Bharat Biotech's nasal vaccine may be used with Covaxin** Sohini Das *Business Standard India* (2021-09-25) <https://www.business-standard.com/article/current-affairs/booster-dose-bharat-biotech-s-nasal-vaccine-may-be-used-with-covaxin-121092500034_1.html>

303. **Covaxin kids trial over, Bharat Biotech to submit data to DCGI next week** The Times of India (2021-09-21) <https://timesofindia.indiatimes.com/india/bharat-biotech-to-submit-covaxin-kids-trials-data-to-dcgi-in-weeks-time/articleshow/86392325.cms>

304. **WHO emergency approval for Covaxin delayed till October 5** India Today <https://www.indiatoday.in/coronavirus-outbreak/video/who-emergency-approval-for-covaxin-delayed-till-october-5-1856178-2021-09-23>

305. **A Snapshot of the Global Race for Vaccines Targeting SARS-CoV-2 and the COVID-19 Pandemic** Colin D Funk, Craig Laferrière, Ali Ardakani *Frontiers in Pharmacology* (2020-06-19) <https://doi.org/gg4hxd> DOI: [10.3389/fphar.2020.00937](https://doi.org/10.3389/fphar.2020.00937) · PMID: [32636754](https://www.ncbi.nlm.nih.gov/pubmed/32636754) · PMCID: [PMC7317023](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7317023)

306. **Moderna’s COVID-19 Vaccine Candidate Meets its Primary Efficacy Endpoint in the First Interim Analysis of the Phase 3 COVE Study | Moderna, Inc.** <https://investors.modernatx.com/news-releases/news-release-details/modernas-covid-19-vaccine-candidate-meets-its-primary-efficacy/>

307. **Vaccines and Related Biological Products Advisory Committee December 17, 2020 Meeting Announcement - 12/17/2020 - 12/17/2020** FDA (2021-01-27) <https://www.fda.gov/advisory-committees/advisory-committee-calendar/vaccines-and-related-biological-products-advisory-committee-december-17-2020-meeting-announcement>

308.  **Vaccines and Related Biological Products Advisory Committee December 17, 2020 Meeting Briefing Document - FDA**  FDA/CBER (2020-12-15) <https://www.fda.gov/media/144434/download>

309. **Moderna Has Completed Case Accrual for First Planned Interim Analysis of its mRNA Vaccine Against COVID-19 (mRNA-1273) | Moderna, Inc.** <https://investors.modernatx.com/news-releases/news-release-details/moderna-has-completed-case-accrual-first-planned-interim/>

310.  **Guidance for Industry: Toxicity Grading Scale for Healthy Adult and Adolescent Volunteers Enrolled in Preventive Vaccine Clinical Trials**  CBER (2018-10-08) <https://www.fda.gov/media/73679/download>

311. **Health Canada Authorizes Moderna COVID-19 Vaccine in Canada | Moderna, Inc.** <https://investors.modernatx.com/news-releases/news-release-details/health-canada-authorizes-moderna-covid-19-vaccine-canada/>

312. **EMA recommends COVID-19 Vaccine Moderna for authorisation in the EU** Daniel GLANVILLE *European Medicines Agency* (2021-01-06) <https://www.ema.europa.eu/en/news/ema-recommends-covid-19-vaccine-moderna-authorisation-eu>

313. **Pfizer and BioNTech Announce Vaccine Candidate Against COVID-19 Achieved Success in First Interim Analysis from Phase 3 Study | Pfizer** <https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-announce-vaccine-candidate-against>

314. **Phase I/II study of COVID-19 RNA vaccine BNT162b1 in adults** Mark J Mulligan, Kirsten E Lyke, Nicholas Kitchin, Judith Absalon, Alejandra Gurtman, Stephen Lockhart, Kathleen Neuzil, Vanessa Raabe, Ruth Bailey, Kena A Swanson, … Kathrin U Jansen *Nature* (2020-08-12) <https://doi.org/gg7ww9> DOI: [10.1038/s41586-020-2639-4](https://doi.org/10.1038/s41586-020-2639-4) · PMID: [32785213](https://www.ncbi.nlm.nih.gov/pubmed/32785213)

315. **COVID-19 vaccine BNT162b1 elicits human antibody and TH1 T cell responses** Ugur Sahin, Alexander Muik, Evelyna Derhovanessian, Isabel Vogler, Lena M Kranz, Mathias Vormehr, Alina Baum, Kristen Pascal, Jasmin Quandt, Daniel Maurus, … Özlem Türeci *Nature* (2020-09-30) <https://doi.org/ghfmb2> DOI: [10.1038/s41586-020-2814-7](https://doi.org/10.1038/s41586-020-2814-7) · PMID: [32998157](https://www.ncbi.nlm.nih.gov/pubmed/32998157)

316. **Safety and Immunogenicity of Two RNA-Based Covid-19 Vaccine Candidates** Edward E Walsh, Robert W Frenck, Ann R Falsey, Nicholas Kitchin, Judith Absalon, Alejandra Gurtman, Stephen Lockhart, Kathleen Neuzil, Mark J Mulligan, Ruth Bailey, … William C Gruber *New England Journal of Medicine* (2020-12-17) <https://doi.org/ghjktx> DOI: [10.1056/nejmoa2027906](https://doi.org/10.1056/nejmoa2027906) · PMID: [33053279](https://www.ncbi.nlm.nih.gov/pubmed/33053279) · PMCID: [PMC7583697](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7583697)

317. **Coronavirus COVID-19 Vaccine Update: Latest Developments | Pfizer** <https://www.pfizer.com/science/coronavirus/vaccine>

318. **Pfizer and BioNTech Conclude Phase 3 Study of COVID-19 Vaccine Candidate, Meeting All Primary Efficacy Endpoints | Pfizer** <https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-conclude-phase-3-study-covid-19-vaccine>

319. **Covid-19: UK approves Pfizer and BioNTech vaccine with rollout due to start next week** Elisabeth Mahase *BMJ* (2020-12-02) <https://doi.org/ghpnhg> DOI: [10.1136/bmj.m4714](https://doi.org/10.1136/bmj.m4714) · PMID: [33268330](https://www.ncbi.nlm.nih.gov/pubmed/33268330)

320. **Covid-19 vaccine: First person receives Pfizer jab in UK** BBC News (2020-12-08) <https://www.bbc.com/news/uk-55227325>

321. **Early effectiveness of COVID-19 vaccination with BNT162b2 mRNA vaccine and ChAdOx1 adenovirus vector vaccine on symptomatic disease, hospitalisations and mortality in older adults in England** Jamie Lopez Bernal, Nick Andrews, Charlotte Gower, Julia Stowe, Chris Robertson, Elise Tessier, Ruth Simmons, Simon Cottrell, Richard Roberts, Mark O’Doherty, … Mary Ramsay *Cold Spring Harbor Laboratory* (2021-03-02) <https://doi.org/gh63t4> DOI: [10.1101/2021.03.01.21252652](https://doi.org/10.1101/2021.03.01.21252652)

322. **The arrival of Sputnik V** Vijay Shankar Balakrishnan *The Lancet Infectious Diseases* (2020-10) <https://doi.org/ghs3sn> DOI: [10.1016/s1473-3099(20)30709-x](https://doi.org/10.1016/s1473-3099(20)30709-x) · PMID: [32979327](https://www.ncbi.nlm.nih.gov/pubmed/32979327) · PMCID: [PMC7511201](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7511201)

323. **Sputnik V COVID-19 vaccine candidate appears safe and effective** Ian Jones, Polly Roy *The Lancet* (2021-02) <https://doi.org/ghx7xz> DOI: [10.1016/s0140-6736(21)00191-4](https://doi.org/10.1016/s0140-6736(21)00191-4) · PMID: [33545098](https://www.ncbi.nlm.nih.gov/pubmed/33545098) · PMCID: [PMC7906719](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7906719)

324. **International seroepidemiology of adenovirus serotypes 5, 26, 35, and 48 in pediatric and adult populations** Dan H Barouch, Sandra V Kik, Gerrit J Weverling, Rebecca Dilan, Sharon L King, Lori F Maxfield, Sarah Clark, David Ng’ang’a, Kara L Brandariz, Peter Abbink, … Jaap Goudsmit *Vaccine* (2011-07) <https://doi.org/bmzpdx> DOI: [10.1016/j.vaccine.2011.05.025](https://doi.org/10.1016/j.vaccine.2011.05.025) · PMID: [21619905](https://www.ncbi.nlm.nih.gov/pubmed/21619905) · PMCID: [PMC3138857](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3138857)

325. **Oxford–AstraZeneca COVID-19 vaccine efficacy** Maria Deloria Knoll, Chizoba Wonodi *The Lancet* (2021-01) <https://doi.org/ghpghz> DOI: [10.1016/s0140-6736(20)32623-4](https://doi.org/10.1016/s0140-6736(20)32623-4) · PMID: [33306990](https://www.ncbi.nlm.nih.gov/pubmed/33306990) · PMCID: [PMC7832220](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7832220)

326. **Lead SARS-CoV-2 Candidate Vaccines: Expectations from Phase III Trials and Recommendations Post-Vaccine Approval** Ebenezer Tumban *Viruses* (2020-12-31) <https://doi.org/gh2z7h> DOI: [10.3390/v13010054](https://doi.org/10.3390/v13010054) · PMID: [33396343](https://www.ncbi.nlm.nih.gov/pubmed/33396343) · PMCID: [PMC7824305](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7824305)

327. **A dangerous rush for vaccines** HHolden Thorp *Science* (2020-08-21) <https://doi.org/gh2pwb> DOI: [10.1126/science.abe3147](https://doi.org/10.1126/science.abe3147) · PMID: [32792466](https://www.ncbi.nlm.nih.gov/pubmed/32792466)

328. **Scientists worry whether Russia's 'Sputnik V' coronavirus vaccine is safe and effective** Berkeley Lovelace Jr *CNBC* (2020-08-11) <https://www.cnbc.com/2020/08/11/scientists-worry-whether-russias-sputnik-v-coronavirus-vaccine-is-safe-and-effective.html>

329. **Russia’s claim of a successful COVID-19 vaccine doesn’t pass the ‘smell test,’ critics say** Jon Cohen *Science* (2020-11-11) <https://doi.org/gh2pwc> DOI: [10.1126/science.abf6791](https://doi.org/10.1126/science.abf6791)

330. **Russia announces positive COVID-vaccine results from controversial trial** Ewen Callaway *Nature* (2020-11-11) <https://doi.org/gh2pv9> DOI: [10.1038/d41586-020-03209-0](https://doi.org/10.1038/d41586-020-03209-0) · PMID: [33177689](https://www.ncbi.nlm.nih.gov/pubmed/33177689)

331. **Covid-19: Russian vaccine efficacy is 91.6%, show phase III trial results** Elisabeth Mahase *BMJ* (2021-02-02) <https://doi.org/gh2pwd> DOI: [10.1136/bmj.n309](https://doi.org/10.1136/bmj.n309) · PMID: [33531342](https://www.ncbi.nlm.nih.gov/pubmed/33531342)

332. **Russia cuts size of COVID-19 vaccine study, stops enrollment** ABC News *ABC News* <https://abcnews.go.com/Health/wireStory/russia-cuts-size-covid-19-vaccine-study-stops-74885458>

333. **About Sputnik V** <https://sputnikvaccine.com/about-vaccine/>

334. **ACTIVE SURVEILLANCE OF THE SPUTNIK V VACCINE IN HEALTH WORKERS** Vanina Pagotto, Analia Ferloni, María Mercedes Soriano, Morena Díaz, Manuel Braguisnky Golde, María Isabel González, Valeria Asprea, Inés Staneloni, Gustavo Vidal, Martin Silveira, … Silvana Figar *Cold Spring Harbor Laboratory* (2021-02-05) <https://doi.org/gprj3m> DOI: [10.1101/2021.02.03.21251071](https://doi.org/10.1101/2021.02.03.21251071)

335. **UPDATE 1-Russia's Sputnik V vaccine found safe in India mid-stage trial -Dr.Reddy's** Reuters (2021-01-11) <https://www.reuters.com/article/health-coronavirus-india-vaccine-idUSL4N2JM2XA>

336. **RDIF, The Gamaleya National Center, AstraZeneca and R-Pharm sign an agreement to cooperate on COVID-19 vaccine development** The Russian Direct Investment Fund (RDIF) <https://www.prnewswire.com/ae/news-releases/rdif-the-gamaleya-national-center-astrazeneca-and-r-pharm-sign-an-agreement-to-cooperate-on-covid-19-vaccine-development-301196874.html>

337. **Open-label, Non-randomized, Non-comparative, Phase II Study in Adult Subjects to Assess Safety and Immunogenicity of Combination of AZD1222, a Non-replicating ChAdOx1 Vector Vaccine, and rAd26-S, a Recombinant Adenovirus Type 26 Component of Gam-COVID-Vac Vaccine, for COVID-19 Prevention** R-Pharm *clinicaltrials.gov* (2021-12-20) <https://clinicaltrials.gov/ct2/show/NCT04686773>

338. **The first registered COVID-19 vaccine** <https://sputnikvaccine.com/>

339. **Johnson & Johnson Initiates Pivotal Global Phase 3 Clinical Trial of Janssen’s COVID-19 Vaccine Candidate | Johnson & Johnson** Content Lab U.S. <https://www.jnj.com/johnson-johnson-initiates-pivotal-global-phase-3-clinical-trial-of-janssens-covid-19-vaccine-candidate>

340. **Low-Dose Ad26.COV2.S Protection Against SARS-CoV-2 Challenge in Rhesus Macaques** Xuan He, Abishek Chandrashekar, Roland Zahn, Frank Wegmann, Jingyou Yu, Noe B Mercado, Katherine McMahan, Amanda J Martinot, Cesar Piedra-Mora, Sidney Beecy, … Dan H Barouch *Cold Spring Harbor Laboratory* (2021-01-27) <https://doi.org/gjhgd3> DOI: [10.1101/2021.01.27.428380](https://doi.org/10.1101/2021.01.27.428380) · PMID: [33532782](https://www.ncbi.nlm.nih.gov/pubmed/33532782) · PMCID: [PMC7852276](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7852276)

341. **Safety and immunogenicity of the Ad26.COV2.S COVID-19 vaccine candidate: interim results of a phase 1/2a, double-blind, randomized, placebo-controlled trial** Jerald Sadoff, Mathieu Le Gars, Georgi Shukarev, Dirk Heerwegh, Carla Truyers, Anne Marit de Groot, Jeroen Stoop, Sarah Tete, Wim Van Damme, Isabel Leroux-Roels, … Hanneke Schuitemaker *Cold Spring Harbor Laboratory* (2020-09-25) <https://doi.org/ghjk2q> DOI: [10.1101/2020.09.23.20199604](https://doi.org/10.1101/2020.09.23.20199604)

342. **Immunogenicity of the Ad26.COV2.S Vaccine for COVID-19** Kathryn E Stephenson, Mathieu Le Gars, Jerald Sadoff, Anne Marit de Groot, Dirk Heerwegh, Carla Truyers, Caroline Atyeo, Carolin Loos, Abishek Chandrashekar, Katherine McMahan, … Dan H Barouch *JAMA* (2021-04-20) <https://doi.org/gjhgdz> DOI: [10.1001/jama.2021.3645](https://doi.org/10.1001/jama.2021.3645) · PMID: [33704352](https://www.ncbi.nlm.nih.gov/pubmed/33704352) · PMCID: [PMC7953339](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7953339)

343. **Correlates of protection against SARS-CoV-2 in rhesus macaques** Katherine McMahan, Jingyou Yu, Noe B Mercado, Carolin Loos, Lisa H Tostanoski, Abishek Chandrashekar, Jinyan Liu, Lauren Peter, Caroline Atyeo, Alex Zhu, … Dan H Barouch *Nature* (2020-12-04) <https://doi.org/fmjk> DOI: [10.1038/s41586-020-03041-6](https://doi.org/10.1038/s41586-020-03041-6) · PMID: [33276369](https://www.ncbi.nlm.nih.gov/pubmed/33276369) · PMCID: [PMC7906955](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7906955)

344. **A Randomized, Double-blind, Placebo-controlled Phase 3 Study to Assess the Efficacy and Safety of Ad26.COV2.S for the Prevention of SARS-CoV-2-mediated COVID-19 in Adults Aged 18 Years and Older** Janssen Vaccines & Prevention B.V. *clinicaltrials.gov* (2022-04-11) <https://clinicaltrials.gov/ct2/show/NCT04505722>

345. **Johnson & Johnson Prepares to Resume Phase 3 ENSEMBLE Trial of its Janssen COVID-19 Vaccine Candidate in the U.S. | Johnson & Johnson** Content Lab U.S. <https://www.jnj.com/our-company/johnson-johnson-prepares-to-resume-phase-3-ensemble-trial-of-its-janssen-covid-19-vaccine-candidate-in-the-us>

346. **B.1.1.7 report** <https://cov-lineages.org/global_report_B.1.1.7.html>

347. **Johnson & Johnson Initiates Second Global Phase 3 Clinical Trial of its Janssen COVID-19 Vaccine Candidate | Johnson & Johnson** Content Lab U.S. <https://www.jnj.com/johnson-johnson-initiates-second-global-phase-3-clinical-trial-of-its-janssen-covid-19-vaccine-candidate>

348. **A Review of the Progress and Challenges of Developing a Vaccine for COVID-19** Omna Sharma, Ali A Sultan, Hong Ding, Chris R Triggle *Frontiers in Immunology* (2020-10-14) <https://doi.org/gh65wd> DOI: [10.3389/fimmu.2020.585354](https://doi.org/10.3389/fimmu.2020.585354) · PMID: [33163000](https://www.ncbi.nlm.nih.gov/pubmed/33163000) · PMCID: [PMC7591699](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7591699)

349. **Recombinant protein vaccines produced in insect cells** Manon MJ Cox *Vaccine* (2012-02) <https://doi.org/fx3mh3> DOI: [10.1016/j.vaccine.2012.01.016](https://doi.org/10.1016/j.vaccine.2012.01.016) · PMID: [22265860](https://www.ncbi.nlm.nih.gov/pubmed/22265860) · PMCID: [PMC7115678](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7115678)

350. **Applications of nanotechnology for immunology** Douglas M Smith, Jakub K Simon, James R Baker Jr *Nature Reviews Immunology* (2013-07-25) <https://doi.org/gfzq8x> DOI: [10.1038/nri3488](https://doi.org/10.1038/nri3488) · PMID: [23883969](https://www.ncbi.nlm.nih.gov/pubmed/23883969) · PMCID: [PMC7097370](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7097370)

351. **Matrix-M™ adjuvant enhances immunogenicity of both protein- and modified vaccinia virus Ankara-based influenza vaccines in mice** Sofia E Magnusson, Arwen F Altenburg, Karin Lövgren Bengtsson, Fons Bosman, Rory D de Vries, Guus F Rimmelzwaan, Linda Stertman *Immunologic Research* (2018-03-28) <https://doi.org/gdd2fw> DOI: [10.1007/s12026-018-8991-x](https://doi.org/10.1007/s12026-018-8991-x) · PMID: [29594879](https://www.ncbi.nlm.nih.gov/pubmed/29594879) · PMCID: [PMC5899102](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5899102)

352. **Immune enhancing properties of the novel Matrix-M™ adjuvant leads to potentiated immune responses to an influenza vaccine in mice** Sofia E Magnusson, Jenny M Reimer, Karin H Karlsson, Lena Lilja, Karin Lövgren Bengtsson, Linda Stertman *Vaccine* (2013-03) <https://doi.org/f2ntg8> DOI: [10.1016/j.vaccine.2013.01.039](https://doi.org/10.1016/j.vaccine.2013.01.039) · PMID: [23384754](https://www.ncbi.nlm.nih.gov/pubmed/23384754)

353. **Intramuscular Matrix-M-adjuvanted virosomal H5N1 vaccine induces high frequencies of multifunctional Th1 CD4+ cells and strong antibody responses in mice** Abdullah S Madhun, Lars R Haaheim, Mona V Nilsen, Rebecca J Cox *Vaccine* (2009-12) <https://doi.org/d6cthn> DOI: [10.1016/j.vaccine.2009.09.044](https://doi.org/10.1016/j.vaccine.2009.09.044) · PMID: [19781678](https://www.ncbi.nlm.nih.gov/pubmed/19781678)

354. **Matrix-M adjuvanted virosomal H5N1 vaccine confers protection against lethal viral challenge in a murine model** Gabriel Pedersen, Diane Major, Sarah Roseby, John Wood, Abdullah S Madhun, Rebecca J Cox *Influenza and Other Respiratory Viruses* (2011-05-09) <https://doi.org/fbkc9w> DOI: [10.1111/j.1750-2659.2011.00256.x](https://doi.org/10.1111/j.1750-2659.2011.00256.x) · PMID: [21668670](https://www.ncbi.nlm.nih.gov/pubmed/21668670) · PMCID: [PMC5780659](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5780659)

355. **Evaluation of a virosomal H5N1 vaccine formulated with Matrix M™ adjuvant in a phase I clinical trial** Rebecca J Cox, Gabriel Pedersen, Abdullah S Madhun, Signe Svindland, Marianne Sævik, Lucy Breakwell, Katja Hoschler, Marieke Willemsen, Laura Campitelli, Jane Kristin Nøstbakken, … Haakon Sjursen *Vaccine* (2011-10) <https://doi.org/dq7db6> DOI: [10.1016/j.vaccine.2011.08.042](https://doi.org/10.1016/j.vaccine.2011.08.042) · PMID: [21864624](https://www.ncbi.nlm.nih.gov/pubmed/21864624)

356. **A 2-Part, Phase 1/2, Randomized, Observer-Blinded Study To Evaluate The Safety And Immunogenicity Of A SARS-CoV-2 Recombinant Spike Protein Nanoparticle Vaccine (SARS-CoV-2 rS) With Or Without MATRIX-M™ Adjuvant In Healthy Subjects** Novavax *clinicaltrials.gov* (2021-12-02) <https://clinicaltrials.gov/ct2/show/NCT04368988>

357. **Evaluation of a SARS-CoV-2 Vaccine NVX-CoV2373 in Younger and Older Adults** Neil Formica, Raburn Mallory, Gary Albert, Michelle Robinson, Joyce S Plested, Iksung Cho, Andreana Robertson, Filip Dubovsky, Gregory M Glenn *Cold Spring Harbor Laboratory* (2021-03-01) <https://doi.org/gjh94p> DOI: [10.1101/2021.02.26.21252482](https://doi.org/10.1101/2021.02.26.21252482)

358. **Dipeptidyl peptidase 4 is a functional receptor for the emerging human coronavirus-EMC** VStalin Raj, Huihui Mou, Saskia L Smits, Dick HW Dekkers, Marcel A Müller, Ronald Dijkman, Doreen Muth, Jeroen AA Demmers, Ali Zaki, Ron AM Fouchier, … Bart L Haagmans *Nature* (2013-03) <https://doi.org/f4qf89> DOI: [10.1038/nature12005](https://doi.org/10.1038/nature12005) · PMID: [23486063](https://www.ncbi.nlm.nih.gov/pubmed/23486063) · PMCID: [PMC7095326](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7095326)

359. **Molecular basis of binding between novel human coronavirus MERS-CoV and its receptor CD26** Guangwen Lu, Yawei Hu, Qihui Wang, Jianxun Qi, Feng Gao, Yan Li, Yanfang Zhang, Wei Zhang, Yuan Yuan, Jinku Bao, … George F Gao *Nature* (2013-07-07) <https://doi.org/m8z> DOI: [10.1038/nature12328](https://doi.org/10.1038/nature12328) · PMID: [23831647](https://www.ncbi.nlm.nih.gov/pubmed/23831647) · PMCID: [PMC7095341](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7095341)

360. **The Receptor Binding Domain of the New Middle East Respiratory Syndrome Coronavirus Maps to a 231-Residue Region in the Spike Protein That Efficiently Elicits Neutralizing Antibodies** Huihui Mou, VStalin Raj, Frank JM van Kuppeveld, Peter JM Rottier, Bart L Haagmans, Berend Jan Bosch *Journal of Virology* (2013-08-15) <https://doi.org/ggq9rg> DOI: [10.1128/jvi.01277-13](https://doi.org/10.1128/jvi.01277-13) · PMID: [23785207](https://www.ncbi.nlm.nih.gov/pubmed/23785207) · PMCID: [PMC3754068](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3754068)

361. **A Truncated Receptor-Binding Domain of MERS-CoV Spike Protein Potently Inhibits MERS-CoV Infection and Induces Strong Neutralizing Antibody Responses: Implication for Developing Therapeutics and Vaccines** Lanying Du, Zhihua Kou, Cuiqing Ma, Xinrong Tao, Lili Wang, Guangyu Zhao, Yaoqing Chen, Fei Yu, Chien-Te K Tseng, Yusen Zhou, Shibo Jiang *PLoS ONE* (2013-12-04) <https://doi.org/gk657p> DOI: [10.1371/journal.pone.0081587](https://doi.org/10.1371/journal.pone.0081587) · PMID: [24324708](https://www.ncbi.nlm.nih.gov/pubmed/24324708) · PMCID: [PMC3852489](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3852489)

362. **Identification of an ideal adjuvant for receptor-binding domain-based subunit vaccines against Middle East respiratory syndrome coronavirus** Naru Zhang, Rudragouda Channappanavar, Cuiqing Ma, Lili Wang, Jian Tang, Tania Garron, Xinrong Tao, Sumaiya Tasneem, Lu Lu, Chien-Te K Tseng, … Lanying Du *Cellular & Molecular Immunology* (2015-02-02) <https://doi.org/f8vdhn> DOI: [10.1038/cmi.2015.03](https://doi.org/10.1038/cmi.2015.03) · PMID: [25640653](https://www.ncbi.nlm.nih.gov/pubmed/25640653) · PMCID: [PMC4786625](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4786625)

363. **Defining trained immunity and its role in health and disease** Mihai G Netea, Jorge Domínguez-Andrés, Luis B Barreiro, Triantafyllos Chavakis, Maziar Divangahi, Elaine Fuchs, Leo AB Joosten, Jos WM van der Meer, Musa M Mhlanga, Willem JM Mulder, … Eicke Latz *Nature Reviews Immunology* (2020-03-04) <https://doi.org/gg28pr> DOI: [10.1038/s41577-020-0285-6](https://doi.org/10.1038/s41577-020-0285-6) · PMID: [32132681](https://www.ncbi.nlm.nih.gov/pubmed/32132681) · PMCID: [PMC7186935](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7186935)

364. **Trained Immunity: a Tool for Reducing Susceptibility to and the Severity of SARS-CoV-2 Infection** Mihai G Netea, Evangelos J Giamarellos-Bourboulis, Jorge Domínguez-Andrés, Nigel Curtis, Reinout van Crevel, Frank L van de Veerdonk, Marc Bonten *Cell* (2020-05) <https://doi.org/gg2584> DOI: [10.1016/j.cell.2020.04.042](https://doi.org/10.1016/j.cell.2020.04.042) · PMID: [32437659](https://www.ncbi.nlm.nih.gov/pubmed/32437659) · PMCID: [PMC7196902](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7196902)

365. **Reducing Health Care Workers Absenteeism in Covid-19 Pandemic Through BCG Vaccine - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04328441>

366. **Application of BCG Vaccine for Immune-prophylaxis Among Egyptian Healthcare Workers During the Pandemic of COVID-19** Adel Khattab *clinicaltrials.gov* (2020-04-17) <https://clinicaltrials.gov/ct2/show/NCT04350931>

367. **Performance Evaluation of BCG Vaccination in Healthcare Personnel to Reduce the Severity of SARS-COV-2 Infection in Medellín, Colombia, 2020** Universidad de Antioquia *clinicaltrials.gov* (2020-11-24) <https://clinicaltrials.gov/ct2/show/NCT04362124>

368. **COVID-19: BCG As Therapeutic Vaccine, Transmission Limitation, and Immunoglobulin Enhancement - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04369794>

369. **Using BCG Vaccine to Protect Health Care Workers in the COVID-19 Pandemic - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04373291>

370. **Reducing Morbidity and Mortality in Health Care Workers Exposed to SARS-CoV-2 by Enhancing Non-specific Immune Responses Through Bacillus Calmette-Guérin Vaccination, a Randomized Controlled Trial** TASK Applied Science *clinicaltrials.gov* (2020-05-06) <https://clinicaltrials.gov/ct2/show/NCT04379336>

371. **Randomized Controlled Trial Evaluating the Efficacy of Vaccination With Bacillus Calmette and Guérin (BCG) in the Prevention of COVID-19 Via the Strengthening of Innate Immunity in Health Care Workers** Assistance Publique - Hôpitaux de Paris *clinicaltrials.gov* (2020-08-17) <https://clinicaltrials.gov/ct2/show/NCT04384549>

372. **Study to Assess VPM1002 in Reducing Healthcare Professionals' Absenteeism in COVID-19 Pandemic - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04387409>

373. **A Randomized Clinical Trial for Enhanced Trained Immune Responses Through Bacillus Calmette-Guérin Vaccination to Prevent Infections by COVID-19: The ACTIVATE II Trial** Hellenic Institute for the Study of Sepsis *clinicaltrials.gov* (2020-07-10) <https://clinicaltrials.gov/ct2/show/NCT04414267>

374. **Reducing Hospital Admission of Elderly in SARS-CoV-2 Pandemic Via the Induction of Trained Immunity by Bacillus Calmette-Guérin Vaccination, a Randomized Controlled Trial** Radboud University *clinicaltrials.gov* (2020-06-03) <https://clinicaltrials.gov/ct2/show/NCT04417335>

375. **Study to Assess VPM1002 in Reducing Hospital Admissions and/or Severe Respiratory Infectious Diseases in Elderly in COVID-19 Pandemic - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04435379>

376. **Efficacy and Safety of VPM1002 in Reducing SARS-CoV-2 (COVID-19) Infection Rate and Severity - Full Text View - ClinicalTrials.gov** <https://clinicaltrials.gov/ct2/show/NCT04439045>

377. **Complex Immune Dysregulation in COVID-19 Patients with Severe Respiratory Failure** Evangelos J Giamarellos-Bourboulis, Mihai G Netea, Nikoletta Rovina, Karolina Akinosoglou, Anastasia Antoniadou, Nikolaos Antonakos, Georgia Damoraki, Theologia Gkavogianni, Maria-Evangelia Adami, Paraskevi Katsaounou, … Antonia Koutsoukou *Cell Host & Microbe* (2020-06) <https://doi.org/ggthxs> DOI: [10.1016/j.chom.2020.04.009](https://doi.org/10.1016/j.chom.2020.04.009) · PMID: [32320677](https://www.ncbi.nlm.nih.gov/pubmed/32320677) · PMCID: [PMC7172841](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7172841)

378. **The Innate Immune System: Fighting on the Front Lines or Fanning the Flames of COVID-19?** Julia L McKechnie, Catherine A Blish *Cell Host & Microbe* (2020-06) <https://doi.org/gg28pq> DOI: [10.1016/j.chom.2020.05.009](https://doi.org/10.1016/j.chom.2020.05.009) · PMID: [32464098](https://www.ncbi.nlm.nih.gov/pubmed/32464098) · PMCID: [PMC7237895](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7237895)

379. **Type I and Type III Interferons – Induction, Signaling, Evasion, and Application to Combat COVID-19** Annsea Park, Akiko Iwasaki *Cell Host & Microbe* (2020-06) <https://doi.org/gg2ccp> DOI: [10.1016/j.chom.2020.05.008](https://doi.org/10.1016/j.chom.2020.05.008) · PMID: [32464097](https://www.ncbi.nlm.nih.gov/pubmed/32464097) · PMCID: [PMC7255347](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7255347)

380. **Viral Mutation Rates** Rafael Sanjuán, Miguel R Nebot, Nicola Chirico, Louis M Mansky, Robert Belshaw *Journal of Virology* (2010-10) <https://doi.org/bc7c55> DOI: [10.1128/jvi.00694-10](https://doi.org/10.1128/jvi.00694-10) · PMID: [20660197](https://www.ncbi.nlm.nih.gov/pubmed/20660197) · PMCID: [PMC2937809](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2937809)

381. **SARS-CoV-2 and influenza: a comparative overview and treatment implications** Laura D Manzanares-Meza, Oscar Medina-Contreras *Boletín Médico del Hospital Infantil de México* (2020-10-23) <https://doi.org/gjj2n7> DOI: [10.24875/bmhim.20000183](https://doi.org/10.24875/bmhim.20000183) · PMID: [33064680](https://www.ncbi.nlm.nih.gov/pubmed/33064680)

382. **Influenza evolution and H3N2 vaccine effectiveness, with application to the 2014/2015 season** Xi Li, Michael W Deem *Protein Engineering Design and Selection* (2016-06-16) <https://doi.org/f856v5> DOI: [10.1093/protein/gzw017](https://doi.org/10.1093/protein/gzw017) · PMID: [27313229](https://www.ncbi.nlm.nih.gov/pubmed/27313229) · PMCID: [PMC4955871](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4955871)

383. **Neutralizing Activity of BNT162b2-Elicited Serum** Yang Liu, Jianying Liu, Hongjie Xia, Xianwen Zhang, Camila R Fontes-Garfias, Kena A Swanson, Hui Cai, Ritu Sarkar, Wei Chen, Mark Cutler, … Pei-Yong Shi *New England Journal of Medicine* (2021-04-15) <https://doi.org/fwsc> DOI: [10.1056/nejmc2102017](https://doi.org/10.1056/nejmc2102017) · PMID: [33684280](https://www.ncbi.nlm.nih.gov/pubmed/33684280) · PMCID: [PMC7944950](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7944950)

384. **Covid-19 vaccine effectiveness affected by variants** Pharmaceutical Technology (2021-03-03) <https://www.pharmaceutical-technology.com/marketdata/covid-19-vaccine-effectiveness-affected-by-variants/>

385. **The effects of virus variants on COVID-19 vaccines** <https://www.who.int/news-room/feature-stories/detail/the-effects-of-virus-variants-on-covid-19-vaccines>

386. **Predicting Influenza H3N2 Vaccine Efficacy From Evolution of the Dominant Epitope** Melia E Bonomo, Michael W Deem *Clinical Infectious Diseases* (2018-04-17) <https://doi.org/gf33js> DOI: [10.1093/cid/ciy323](https://doi.org/10.1093/cid/ciy323) · PMID: [29672670](https://www.ncbi.nlm.nih.gov/pubmed/29672670)

387. **Looking beyond COVID-19 vaccine phase 3 trials** Jerome H Kim, Florian Marks, John D Clemens *Nature Medicine* (2021-01-19) <https://doi.org/ght28p> DOI: [10.1038/s41591-021-01230-y](https://doi.org/10.1038/s41591-021-01230-y) · PMID: [33469205](https://www.ncbi.nlm.nih.gov/pubmed/33469205)

388. **The challenges of distributing COVID-19 vaccinations** Melinda C Mills, David Salisbury *EClinicalMedicine* (2021-01) <https://doi.org/gh77b5> DOI: [10.1016/j.eclinm.2020.100674](https://doi.org/10.1016/j.eclinm.2020.100674) · PMID: [33319186](https://www.ncbi.nlm.nih.gov/pubmed/33319186) · PMCID: [PMC7725651](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7725651)

389. **An ethical framework for global vaccine allocation** Ezekiel J Emanuel, Govind Persad, Adam Kern, Allen Buchanan, Cécile Fabre, Daniel Halliday, Joseph Heath, Lisa Herzog, RJ Leland, Ephrem T Lemango, … Henry S Richardson *Science* (2020-09-03) <https://doi.org/ghz7k6> DOI: [10.1126/science.abe2803](https://doi.org/10.1126/science.abe2803) · PMID: [32883884](https://www.ncbi.nlm.nih.gov/pubmed/32883884) · PMCID: [PMC8691258](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8691258)

390. **Vaccine optimization for COVID-19: Who to vaccinate first?** Laura Matrajt, Julia Eaton, Tiffany Leung, Elizabeth R Brown *Science Advances* (2021-02-05) <https://doi.org/ghz7k7> DOI: [10.1126/sciadv.abf1374](https://doi.org/10.1126/sciadv.abf1374) · PMID: [33536223](https://www.ncbi.nlm.nih.gov/pubmed/33536223) · PMCID: [PMC8128110](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8128110)

391. **Model-informed COVID-19 vaccine prioritization strategies by age and serostatus** Kate M Bubar, Kyle Reinholt, Stephen M Kissler, Marc Lipsitch, Sarah Cobey, Yonatan H Grad, Daniel B Larremore *Science* (2021-02-26) <https://doi.org/ght4xk> DOI: [10.1126/science.abe6959](https://doi.org/10.1126/science.abe6959) · PMID: [33479118](https://www.ncbi.nlm.nih.gov/pubmed/33479118) · PMCID: [PMC7963218](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7963218)

392. **Strategic spatiotemporal vaccine distribution increases the survival rate in an infectious disease like Covid-19** Jens Grauer, Hartmut Löwen, Benno Liebchen *Scientific Reports* (2020-12) <https://doi.org/ghq7vp> DOI: [10.1038/s41598-020-78447-3](https://doi.org/10.1038/s41598-020-78447-3) · PMID: [33299029](https://www.ncbi.nlm.nih.gov/pubmed/33299029) · PMCID: [PMC7726577](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7726577)

393. **How should we conduct pandemic vaccination?** Jane Williams, Chris Degeling, Jodie McVernon, Angus Dawson *Vaccine* (2021-02) <https://doi.org/gh77b7> DOI: [10.1016/j.vaccine.2020.12.059](https://doi.org/10.1016/j.vaccine.2020.12.059) · PMID: [33423839](https://www.ncbi.nlm.nih.gov/pubmed/33423839) · PMCID: [PMC7792561](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7792561)

394. **Vaccine ethics: an ethical framework for global distribution of COVID-19 vaccines** Nancy S Jecker, Aaron G Wightman, Douglas S Diekema *Journal of Medical Ethics* (2021-02-16) <https://doi.org/gh77cg> DOI: [10.1136/medethics-2020-107036](https://doi.org/10.1136/medethics-2020-107036) · PMID: [33593876](https://www.ncbi.nlm.nih.gov/pubmed/33593876) · PMCID: [PMC7887861](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7887861)

395. **Optimal SARS-CoV-2 vaccine allocation using real-time seroprevalence estimates in Rhode Island and Massachusetts** Thu Nguyen-Anh Tran, Nathan Wikle, Joseph Albert, Haider Inam, Emily Strong, Karel Brinda, Scott M Leighow, Fuhan Yang, Sajid Hossain, Justin R Pritchard, … Maciej F Boni *Cold Spring Harbor Laboratory* (2021-01-15) <https://doi.org/gh77b9> DOI: [10.1101/2021.01.12.21249694](https://doi.org/10.1101/2021.01.12.21249694) · PMID: [33469599](https://www.ncbi.nlm.nih.gov/pubmed/33469599) · PMCID: [PMC7814845](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7814845)

396. **Coronavirus Pandemic (COVID-19)** Hannah Ritchie, Edouard Mathieu, Lucas Rodés-Guirao, Cameron Appel, Charlie Giattino, Esteban Ortiz-Ospina, Joe Hasell, Bobbie Macdonald, Diana Beltekian, Max Roser *Our World in Data* (2020-03-05) <https://ourworldindata.org/covid-vaccination-policy>

397. **Tracking Coronavirus Vaccinations Around the World** Josh Holder *The New York Times* (2021-01-29) <https://www.nytimes.com/interactive/2021/world/covid-vaccinations-tracker.html>

398. **Bloomberg - Are you a robot?** <https://www.bloomberg.com/tosv2.html?vid=&uuid=675bb367-c4b7-11ec-8801-68557a734c6e&url=L2dyYXBoaWNzL2NvdmlkLXZhY2NpbmUtdHJhY2tlci1nbG9iYWwtZGlzdHJpYnV0aW9u>

399. **One Vaccine Side Effect: Global Economic Inequality** Peter S Goodman *The New York Times* (2020-12-25) <https://www.nytimes.com/2020/12/25/business/coronavirus-vaccines-global-economy.html>

400. **Vaccine development and approval in Canada** Health Canada (2020-12-08) <https://www.canada.ca/en/health-canada/services/drugs-health-products/covid19-industry/drugs-vaccines-treatments/vaccines/development-approval-infographic.html>

401. **Vaccines and treatments for COVID-19: Safety after authorization** Public Health Agency of Canada (2020-12-03) <https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/prevention-risks/covid-19-vaccine-treatment/safety-after-authorization.html>

402. **Drug and vaccine authorizations for COVID-19: Applications received** Health Canada (2020-09-17) <https://www.canada.ca/en/health-canada/services/drugs-health-products/covid19-industry/drugs-vaccines-treatments/authorization/applications.html>

403. **An earlier end date for vaccination campaign is 'possible', Trudeau says | CBC News** John Paul Tasker ·CBC News · *CBC* <https://www.cbc.ca/news/politics/trudeau-possible-vaccination-campaign-ends-sooner-1.5934994>

404. **The Advisory Committee on Immunization Practices’ Interim Recommendation for Allocating Initial Supplies of COVID-19 Vaccine — United States, 2020** Kathleen Dooling, Nancy McClung, Mary Chamberland, Mona Marin, Megan Wallace, Beth P Bell, Grace M Lee, HKeipp Talbot, José R Romero, Sara E Oliver *MMWR. Morbidity and Mortality Weekly Report* (2020-12-11) <https://doi.org/gjkxrm> DOI: [10.15585/mmwr.mm6949e1](https://doi.org/10.15585/mmwr.mm6949e1) · PMID: [33301429](https://www.ncbi.nlm.nih.gov/pubmed/33301429) · PMCID: [PMC7737687](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7737687)

405. **The Advisory Committee on Immunization Practices’ Interim Recommendation for Use of Pfizer-BioNTech COVID-19 Vaccine — United States, December 2020** Sara E Oliver, Julia W Gargano, Mona Marin, Megan Wallace, Kathryn G Curran, Mary Chamberland, Nancy McClung, Doug Campos-Outcalt, Rebecca L Morgan, Sarah Mbaeyi, … Kathleen Dooling *MMWR. Morbidity and Mortality Weekly Report* (2020-12-18) <https://doi.org/ghvnsf> DOI: [10.15585/mmwr.mm6950e2](https://doi.org/10.15585/mmwr.mm6950e2) · PMID: [33332292](https://www.ncbi.nlm.nih.gov/pubmed/33332292) · PMCID: [PMC7745957](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7745957)

406. **US administers 1st doses of Pfizer coronavirus vaccine** ABC News *ABC News* <https://abcnews.go.com/US/us-administer-1st-doses-pfizer-coronavirus-vaccine/story?id=74703018>

407. **The Advisory Committee on Immunization Practices’ Interim Recommendation for Use of Moderna COVID-19 Vaccine — United States, December 2020** Sara E Oliver, Julia W Gargano, Mona Marin, Megan Wallace, Kathryn G Curran, Mary Chamberland, Nancy McClung, Doug Campos-Outcalt, Rebecca L Morgan, Sarah Mbaeyi, … Kathleen Dooling *MMWR. Morbidity and Mortality Weekly Report* (2021-01-01) <https://doi.org/gh77ch> DOI: [10.15585/mmwr.mm695152e1](https://doi.org/10.15585/mmwr.mm695152e1) · PMID: [33382675](https://www.ncbi.nlm.nih.gov/pubmed/33382675)

408. **The Advisory Committee on Immunization Practices’ Updated Interim Recommendation for Allocation of COVID-19 Vaccine — United States, December 2020** Kathleen Dooling, Mona Marin, Megan Wallace, Nancy McClung, Mary Chamberland, Grace M Lee, HKeipp Talbot, José R Romero, Beth P Bell, Sara E Oliver *MMWR. Morbidity and Mortality Weekly Report* (2021-01-01) <https://doi.org/ghqfvr> DOI: [10.15585/mmwr.mm695152e2](https://doi.org/10.15585/mmwr.mm695152e2) · PMID: [33382671](https://www.ncbi.nlm.nih.gov/pubmed/33382671)

409. **The Moderna vaccine is now in some Americans' arms as Covid-19 cases in the US pass 18 million** Madeline Holcombe Almasy Holly Yan,Steve *CNN* (2020-12-21) <https://www.cnn.com/2020/12/21/health/us-coronavirus-monday/index.html>

410. **Janssen COVID-19 Vaccine** Office of the Commissioner *FDA* (2022-04-07) <https://www.fda.gov/emergency-preparedness-and-response/coronavirus-disease-2019-covid-19/janssen-covid-19-vaccine>

411. **The Advisory Committee on Immunization Practices’ Interim Recommendation for Use of Janssen COVID-19 Vaccine — United States, February 2021** Sara E Oliver, Julia W Gargano, Heather Scobie, Megan Wallace, Stephen C Hadler, Jessica Leung, Amy E Blain, Nancy McClung, Doug Campos-Outcalt, Rebecca L Morgan, … Kathleen Dooling *MMWR. Morbidity and Mortality Weekly Report* (2021-03-05) <https://doi.org/gh77cj> DOI: [10.15585/mmwr.mm7009e4](https://doi.org/10.15585/mmwr.mm7009e4) · PMID: [33661860](https://www.ncbi.nlm.nih.gov/pubmed/33661860) · PMCID: [PMC7948932](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7948932)

412. **WHO adds Janssen vaccine to list of safe and effective emergency tools against COVID-19** <https://www.who.int/news/item/12-03-2021-who-adds-janssen-vaccine-to-list-of-safe-and-effective-emergency-tools-against-covid-19>

413. **COVID-19 Vaccines** Assistant Secretary for Public Affairs (ASPA) *HHS.gov* (2020-12-12) <https://www.hhs.gov/coronavirus/covid-19-vaccines/index.html>

414. **Biden now says US will have enough vaccine for every adult by the end of May | CNN Politics** Kevin Liptak Harwood Jeff Zeleny,John *CNN* (2021-03-02) <https://www.cnn.com/2021/03/02/politics/biden-merck-johnson--johnson-vaccine/index.html>

415. **Covid-19: Was US vaccine rollout a 'dismal failure' under Trump?** BBC News (2021-01-26) <https://www.bbc.com/news/world-us-canada-55721437>

416. **Structured to Fail: Lessons from the Trump Administration's Faulty Pandemic Planning and Response** Alejandro E Camacho, Robert L Glicksman (2021-01-21) <https://papers.ssrn.com/abstract=3770368>

417. **The US Regulatory System and COVID-19 Vaccines** Joshua M Sharfstein, Jesse L Goodman, Luciana Borio *JAMA* (2021-03-23) <https://doi.org/gh77b3> DOI: [10.1001/jama.2021.1961](https://doi.org/10.1001/jama.2021.1961) · PMID: [33587124](https://www.ncbi.nlm.nih.gov/pubmed/33587124)

418. **South Africa starts administering Janssen COVID-19 vaccine to health workers** Rachel Arthur *BioPharma-Reporter* (2021-02-18) <https://www.biopharma-reporter.com/Article/2021/02/18/South-Africa-starts-administering-Janssen-COVID-19-vaccine-to-health-workers>

419. **EMA receives application for conditional marketing authorisation of COVID-19 Vaccine Janssen** EMA *European Medicines Agency* (2021-02-16) <https://www.ema.europa.eu/en/news/ema-receives-application-conditional-marketing-authorisation-covid-19-vaccine-janssen>

420. **Merck will help make Johnson & Johnson coronavirus vaccine as rivals team up to help Biden accelerate shots** Washington Post <https://www.washingtonpost.com/health/2021/03/02/merck-johnson-and-johnson-covid-vaccine-partnership/>

421. **The UK has approved a COVID vaccine — here’s what scientists now want to know** Heidi Ledford, David Cyranoski, Richard Van Noorden *Nature* (2020-12-03) <https://doi.org/gh4xmm> DOI: [10.1038/d41586-020-03441-8](https://doi.org/10.1038/d41586-020-03441-8) · PMID: [33288887](https://www.ncbi.nlm.nih.gov/pubmed/33288887)

422. **EMA recommends first COVID-19 vaccine for authorisation in the EU** EMA *European Medicines Agency* (2020-12-21) <https://www.ema.europa.eu/en/news/ema-recommends-first-covid-19-vaccine-authorisation-eu>

423. **Regulatory approval of COVID-19 Vaccine AstraZeneca** GOV.UK <https://www.gov.uk/government/publications/regulatory-approval-of-covid-19-vaccine-astrazeneca>

424. **EMA recommends COVID-19 Vaccine AstraZeneca for authorisation in the EU** EMA *European Medicines Agency* (2021-01-29) <https://www.ema.europa.eu/en/news/ema-recommends-covid-19-vaccine-astrazeneca-authorisation-eu>

425. **Covid: Brian Pinker, 82, first to get Oxford-AstraZeneca vaccine** BBC News (2021-01-04) <https://www.bbc.com/news/uk-55525542>

426. **Spikevax (previously COVID-19 Vaccine Moderna)** EMA *European Medicines Agency* (2021-01-04) <https://www.ema.europa.eu/en/medicines/human/EPAR/spikevax>

427. **Regulatory approval of Spikevax (formerly COVID-19 Vaccine Moderna)** GOV.UK <https://www.gov.uk/government/publications/regulatory-approval-of-covid-19-vaccine-moderna>

428. **Bloomberg - Are you a robot?** <https://www.bloomberg.com/tosv2.html?vid=&uuid=67a10270-c4b7-11ec-aa2c-6c5066664466&url=L25ld3MvYXJ0aWNsZXMvMjAyMC0xMi0wMi93aXRoaW4taG91cnMtb2YtdS1rLXB1dGluLW9yZGVycy1zdGFydC1vZi1tYXNzLWNvdmlkLTE5LXNob3Rz>

429. **Facing Record Covid-19 Case Rise, Russia Rolls Out Sputnik V Vaccine** James Rodgers *Forbes* <https://www.forbes.com/sites/jamesrodgerseurope/2020/12/05/facing-record-covid-19-case-rise-russia-rolls-out-sputnik-v-vaccine/>

430. **Clarification on Sputnik V vaccine in the EU approval process** EMA *European Medicines Agency* (2021-02-10) <https://www.ema.europa.eu/en/news/clarification-sputnik-v-vaccine-eu-approval-process>

431. **Countries are lining up for Russia's once-scorned Sputnik vaccine after strong efficacy results** Fortune <https://fortune.com/2021/02/08/international-sputnik-russia-demand/>

432. **RDIF announces delivery of the first batch of Sputnik V vaccine to Venezuela for clinical trials** <https://sputnikvaccine.com/newsroom/pressreleases/rdif-announces-delivery-of-the-first-batch-of-sputnik-v-vaccine-to-venezuela-for-clinical-trials/>

433. **Unable to get U.S. vaccines, world turns to Russia and China** Ryan Heath *POLITICO* <https://www.politico.com/news/2021/02/25/global-vaccine-public-relations-war-471665>

434. **Germany moves to bring Russian vaccine into EU orbit** France 24 (2021-02-03) <https://www.france24.com/en/live-news/20210203-germany-moves-to-bring-russian-vaccine-into-eu-orbit>

435. **Russia approves its third COVID-19 vaccine, CoviVac** Reuters (2021-02-20) <https://www.reuters.com/article/us-health-coronavirus-russia-vaccine-idUSKBN2AK07H>

436. **Intranasal Vaccine For Covid-19 | Bharat Biotech** <https://www.bharatbiotech.com/intranasal-vaccine.html>

437. **Novavax aims for 2 billion COVID-19 vaccine doses with expanded India deal** Reuters (2020-09-15) <https://www.reuters.com/article/health-coronavirus-novavax-idUSKBN2661PI>

438. <https://ir.novavax.com/news-releases/news-release-details/novavax-announces-expanded-collaboration-and-license-agreement>

439. **Sputnik Light: What we know about the new Covid vaccine in India** BBC News (2022-02-07) <https://www.bbc.com/news/world-asia-india-55748124>

440. **Vaccine Supply** <https://www.mea.gov.in/vaccine-supply.htm>

441. **Coronavirus Vaccine Tracker** Carl Zimmer, Jonathan Corum, Sui-Lee Wee, Matthew Kristoffersen *The New York Times* (2020-06-10) <https://www.nytimes.com/interactive/2020/science/coronavirus-vaccine-tracker.html>

442. **China Wanted to Show Off Its Vaccines. It’s Backfiring.** Sui-Lee Wee *The New York Times* (2021-01-25) <https://www.nytimes.com/2021/01/25/business/china-covid-19-vaccine-backlash.html>

443. **Coronavirus Vaccine Tracker** Carl Zimmer, Jonathan Corum, Sui-Lee Wee, Matthew Kristoffersen *The New York Times* (2020-06-10) <https://www.nytimes.com/interactive/2020/science/coronavirus-vaccine-tracker.html>

444. **Coronavirus Vaccine Tracker** Carl Zimmer, Jonathan Corum, Sui-Lee Wee, Matthew Kristoffersen *The New York Times* (2020-06-10) <https://www.nytimes.com/interactive/2020/science/coronavirus-vaccine-tracker.html>

445. **Philippines receives COVID-19 vaccine after delays** ABC News *ABC News* <https://abcnews.go.com/Health/wireStory/philippines-receive-covid-19-vaccine-delays-76163594>

446. **China’s Covid-19 Vaccine Makers Struggle to Meet Demand** Chao Deng in Taipei and Jared Malsin in Dubai *Wall Street Journal* (2021-02-10) <https://www.wsj.com/articles/chinas-covid-19-vaccine-makers-struggle-to-meet-demand-11612958560>

447. **With First Dibs on Vaccines, Rich Countries Have ‘Cleared the Shelves’** Megan Twohey, Keith Collins, Katie Thomas *The New York Times* (2020-12-15) <https://www.nytimes.com/2020/12/15/us/coronavirus-vaccine-doses-reserved.html>

448. **Covid-19 vaccinations: African nations miss WHO target** BBC News (2021-12-31) <https://www.bbc.com/news/56100076>

449. **International Collaboration to Ensure Equitable Access to Vaccines for COVID‐19: The ACT‐Accelerator and the COVAX Facility** MARK ECCLESTON‐TURNER, HARRY UPTON *The Milbank Quarterly* (2021-03-02) <https://doi.org/gh77cc> DOI: [10.1111/1468-0009.12503](https://doi.org/10.1111/1468-0009.12503) · PMID: [33650737](https://www.ncbi.nlm.nih.gov/pubmed/33650737) · PMCID: [PMC8014072](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8014072)

450. **Fair allocation mechanism for COVID-19 vaccines through the COVAX Facility** <https://www.who.int/publications/m/item/fair-allocation-mechanism-for-covid-19-vaccines-through-the-covax-facility>

451. **Global plan seeks to promote vaccine equity, spread risks** Kai Kupferschmidt *Science* (2020-07-31) <https://doi.org/gh77cd> DOI: [10.1126/science.369.6503.489](https://doi.org/10.1126/science.369.6503.489) · PMID: [32732400](https://www.ncbi.nlm.nih.gov/pubmed/32732400)

452. **Covax must go beyond proportional allocation of covid vaccines to ensure fair and equitable access** Lisa M Herzog, Ole F Norheim, Ezekiel J Emanuel, Matthew S McCoy *BMJ* (2021-01-05) <https://doi.org/gjgqjv> DOI: [10.1136/bmj.m4853](https://doi.org/10.1136/bmj.m4853) · PMID: [33402340](https://www.ncbi.nlm.nih.gov/pubmed/33402340)

453. **COVAX** <https://www.who.int/initiatives/act-accelerator/covax>

454. **Countries now scrambling for COVID-19 vaccines may soon have surpluses to donate** AAAS Articles DO Group *American Association for the Advancement of Science (AAAS)* (2021-08-16) <https://doi.org/gh77cf> DOI: [10.1126/science.abh4476](https://doi.org/10.1126/science.abh4476)

455. **First COVID-19 COVAX vaccine doses administered in Africa** <https://www.who.int/news/item/01-03-2021-first-covid-19-covax-vaccine-doses-administered-in-africa>

456. **Pfizer and BioNTech to Submit Emergency Use Authorization Request Today to the U.S. FDA for COVID-19 Vaccine | Pfizer** <https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-submit-emergency-use-authorization>

457. **Moderna Announces First Participants Dosed in Phase 2/3 Study of COVID-19 Vaccine Candidate in Adolescents | Moderna, Inc.** <https://investors.modernatx.com/news-releases/news-release-details/moderna-announces-first-participants-dosed-phase-23-study-covid/>