Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.

Clinical Microbiology and Infection 28 (2022) 163–177

Contents lists available at ScienceDirect

Clinical Microbiology and Infection

journal homepage: www.clinicalmicrobiologyandinfection.com

Systematic review

Immunological and clinical efficacy of COVID-19 vaccines in immunocompromised populations: a systematic review

Simon Galmiche [1], Liem Binh Luong Nguyen [1], Eric Tartour [2], Xavier de Lamballerie [3], Linda Wittkop [4], Paul Loubet [5], Odile Launay [6,*]

[1] Assistance Publique – Hôpitaux de Paris (AP-HP), CIC Cochin Pasteur, Hôpital Cochin, Paris, France
[2] AP-HP, Immunologie Biologique, Hôpital Européen Georges Pompidou, Paris, France
[3] Aix Marseille Université, IRD 190, INSERM 1207, Unité des Virus Emergents, UVE, IHU Méditerranée Infection, Marseille, France
[4] Institut de Santé Publique d'Epidémiologie et de Développement, INSERM, Bordeaux Population Health Research Center, UMR 1219, Centre d'Investigation Clinique–Epidémiologie Clinique 1401, University of Bordeaux, Service d'Information Médicale, CHU de Bordeaux, Pôle de Santé Publique, Bordeaux, France
[5] INSERM U1047, Department of Infectious and Tropical Diseases, CHU Nîmes, Université Montpellier, Nîmes, France
[6] Université de Paris, Faculté de Médecine Paris Descartes, AP-PH, Inserm, CIC Cochin Pasteur, Paris, France

ARTICLE INFO

Article history:
Received 10 August 2021
Received in revised form
28 September 2021
Accepted 29 September 2021
Available online 17 November 2021

Editor: L. Leibovici

Keywords:
Cancer
COVID-19
Dialysis
Effectiveness
Efficacy
Immunogenicity
SARS-CoV-2 immunocompromised
Solid organ transplant
Vaccine

ABSTRACT

Background: Available data show that COVID-19 vaccines may be less effective in immunocompromised populations, who are at increased risk of severe COVID-19.
Objectives: We conducted a systematic review of literature to assess immunogenicity, efficacy and effectiveness of COVID-19 vaccines in immunocompromised populations.
Data sources: We searched Medline and Embase databases.
Study eligibility criteria, patients, interventions: We included studies of COVID-19 vaccines after complete vaccination in immunocompromised patients until 31 August 2021. Studies with <10 patients, safety data only and case series of breakthrough infections were excluded.
Methods: Risk of bias was assessed via the tool developed by the National Institutes of Health on interventional and observational studies. Immunogenicity was assessed through non-response rate defined as no anti-SARS-CoV-2 spike protein antibodies, efficacy and effectiveness by the relative reduction in risk of SARS-CoV-2 infection or COVID-19. We collected factors associated with the risk of non-response. We presented collected data by immunosuppression type.
Results: We screened 5917 results, included 162 studies. There were 157 on immunogenicity in 25 209 participants, including 7835 cancer or haematological malignancy patients (31.1%), 6302 patients on dialysis (25.0%), 5974 solid organ transplant recipients (23.7%) and 4680 immune-mediated disease patients (18.6%). Proportion of non-responders seemed higher among solid organ transplant recipients (range 18–100%) and patients with haematological malignancy (range 14–61%), and lower in patients with cancer (range 2–36%) and patients on dialysis (range 2–30%). Risk factors for non-response included older age, use of corticosteroids, immunosuppressive or anti-CD20 agent. Ten studies evaluated immunogenicity of an additional dose. Five studies evaluated vaccine efficacy or effectiveness: three on SARS-CoV-2 infection (range 71–81%), one on COVID-19-related hospitalization (62.9%), one had a too small sample size.
Conclusions: This systematic review highlights the risk of low immunogenicity of COVID-19 vaccines in immunocompromised populations, especially solid organ transplant recipients and patients with haematological malignancy. Despite lack of vaccine effectiveness data, enhanced vaccine regimens may be necessary. **Simon Galmiche, Clin Microbiol Infect 2022;28:163**
© 2021 European Society of Clinical Microbiology and Infectious Diseases. Published by Elsevier Ltd. All rights reserved.

* Corresponding author. Odile Launay, CIC Cochin Pasteur, Hôpital Cochin, 27 rue du Faubourg Saint-Jacques, 75014, Paris, France
E-mail address: odile.launay@aphp.fr (O. Launay).

https://doi.org/10.1016/j.cmi.2021.09.036
1198-743X/© 2021 European Society of Clinical Microbiology and Infectious Diseases. Published by Elsevier Ltd. All rights reserved.

Introduction

A set of COVID-19 vaccines has been rapidly developed with high vaccine efficacy in phase 3 studies. However, these large-scale pre-marketing studies provide little information on vaccine efficacy in immunocompromised populations, while current evidence shows an increased risk of severe COVID-19 in patients with cancer [1], solid organ transplant [2,3], end-stage renal disease [4,5] and rheumatic immune-mediated diseases on immunosuppressive treatment [6].

Available data with other vaccines indicate a lower vaccine immunogenicity and efficacy in immunocompromised patients, such as patients undergoing haemodialysis, solid organ transplant recipients [7,8], patients with cancer or haematological malignancy [9,10] and those with autoimmune inflammatory diseases [11], hence raising the concern of potentially decreased immunogenicity and effectiveness of COVID-19 vaccines.

Several studies have been published in the past few months on the immunogenicity of COVID-19 vaccines in different populations of immunocompromised subjects, leading some countries such as France, and more recently the United States, to recommend an additional dose of vaccine [12,13]. We aimed to summarize available evidence on vaccine immunogenicity and factors associated with non-response to vaccine, efficacy and effectiveness in these populations through a systematic review of literature.

Materials and methods

Objectives and outcomes of interest

We conducted a systematic review of literature until 31 August 2021. The main objective was to assess evidence on COVID-19 vaccine immunogenicity, efficacy and effectiveness in immunocompromised populations. The secondary objectives were to determine factors associated with lack of post-vaccine immunity or low post-vaccine antibody titres, elements of cellular response following vaccination and benefits of additional doses.

Outcomes of interest were vaccine efficacy assessed by the relative reduction in risk of COVID-19 in randomized placebo-controlled trials, vaccine effectiveness, assessed by the relative reduction in risk of SARS-CoV-2 infection in observational studies on RT-PCR-confirmed SARS-CoV-2 infections or in relative reduction in risk of SARS-CoV-2-related hospitalizations or death, and immunogenicity assessed by the rate of non-responders defined as no anti-SARS-CoV-2 spike protein antibodies (IgG, total antibodies if IgG unavailable) as per cut-off defined in each study. If only neutralization assay data were available, we defined non-response as absence of neutralizing antibodies as per cut-off defined in the study. Factors associated with lack of post-vaccine immunity or lower post-vaccine antibody titres, compared with the rest of the population of interest or to a control group (if any), were defined according to associations found in each study.

Inclusion and exclusion criteria

We included reports of COVID-19 vaccine immunogenicity, efficacy and effectiveness in any of the following populations: cancer, haematological malignancy, solid organ transplantation, allogenic stem cell transplantation, autoimmune systemic disease, autoimmune organ specific disease, inflammatory bowel disease, sarcoidosis, autoinflammatory disease, multiple sclerosis, neuromyelitis optica spectrum disease, chronic kidney disease, HIV infection, congenital immunodeficiency, patients undergoing immunosuppressive medications, systemic corticosteroids, monoclonal antibodies. We grouped studies by type of immunosuppressed population.

We included studies of various designs and article types (including preprints, given the rapidly evolving evidence in that field): interventional trials, observational studies and original articles, comments, letters and case series. No language restrictions were imposed.

Exclusion criteria were reports of an incomplete vaccination schedule (i.e. only one dose for all available vaccines except the Ad26.COV2.S Janssen vaccine), review or recommendation articles lacking original data, studies reporting only safety data, case reports, case series reporting fewer than ten patients and case series of breakthrough infections.

Search and data extraction strategies

We searched the databases Medline through PubMed and Embase from inception until 31 August 2021. We used a series of key words and their corresponding Mesh terms for the Pubmed search and the same key words as Emtree terms for the Embase search. Full search strategies are available in supplementary material. One investigator (S.G.) screened titles and abstracts for eligibility. Two investigators (S.G., L.B.L.N.) independently read the selected articles to assess eligibility and met to determine final eligibility. A third investigator (O.L.) split the case in case of persistent discrepancy. We screened grey literature (frequent consultation of core clinical journal websites, abstracts of the congresses of international infectious diseases societies, advisory committee on immunization practice presentations regarding COVID-19 vaccines in immunocompromised populations) and references lists of included reports for further studies. One investigator (S.G.) collected the following data from all selected reports: study type, study population, control group (if any), vaccine used, estimated vaccine efficacy or effectiveness, time from completion of vaccination to measurement of immunogenicity, methods for measurement of immunogenicity, cellular response indicators (if any), neutralization indicators (if any), amount and rate of non-responders (to an additional dose of vaccine if any), factors associated with non-response or lower antibody titres (in multivariable analysis, if any, otherwise in univariable analysis). If studies did not report response status after completion of vaccination schedule for their entire study population, we only considered the subpopulations for whom those data were available.

We collected and synthesized data from studies and created graphs using an Excel spreadsheet. We used STATA/IC 15.1 (College Station, Texas, USA) for further data synthesis.

Risk of bias assessment

We assessed risk of bias through the National Institutes of Health (NIH) quality assessment tools for controlled interventional studies and observational cohorts [14]. Two investigators (S.G., L.B.L.N.) independently assessed risk of bias; discrepancy cases were first discussed between the investigators, then split by a third investigator (P.L.) in case of persistent discordance.

Results

We launched searches on 7 June 2021, again on 21 June 2021, and set up daily e-mail alerts on both databases for subsequent days until 31 August 2021. Searches retrieved 3544 results on Medline and 2373 results on Embase, with 525 duplicates. After title and abstract screening, we retained 271 reports. After full-text reading, grey literature and reference list inspection, 162 studies were included from 170 reports (some reports detailed different timepoints of the same study [15–28] (Fig. 1).

Most studies were prone to some bias; 21 of them were estimated of good quality (Tables S1 and S2). Most frequent sources of bias were lack of definition of population from which participants were included, of sample size calculation and of adjustment on potential confounding factors. The studies on vaccine efficacy or effectiveness were all considered of good or fair quality in the risk of bias assessment.

The vast majority of included studies evaluated vaccines developed by Pfizer (BNT162b2) or Moderna (mRNA-1273). Thirteen studies included patients who received the vaccine developed by Janssen (Ad26.COV2.S) [25–27,29–40], nine included patients vaccinated with the AstraZeneca vaccine (ChAdOx1) [41–49], three included patients receiving the CoronaVac vaccine (Sinovac Biotech) [50–52], and one randomized controlled trial evaluated

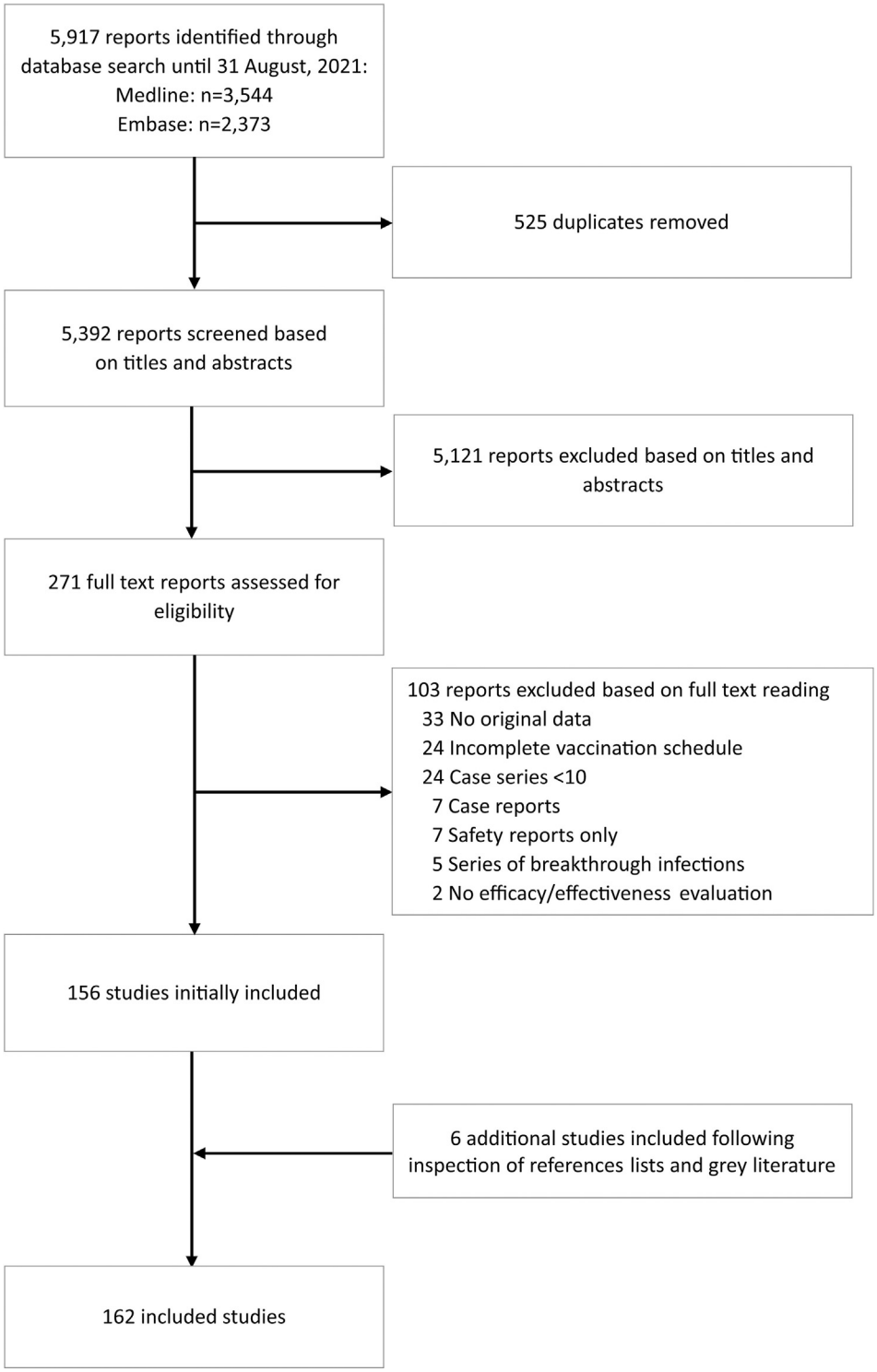

Fig. 1. Flow chart of study selection.

the vaccine developed by Novavax (NVX-CoV2373) vaccine [53]. One study included patients receiving the BBV152-Covaxin (Bharat Biotech) vaccine [44] and one included patients receiving the BBIBP-CorV (Sinopharm) vaccine [54].

Methods of measurement of post-vaccine immunity

Most studies assessed anti-SARS-CoV-2 immunity through an immunoassay to detect antibodies targeted at the spike protein, including some targeting specifically the receptor-binding domain (RBD) of the spike protein. Thirty studies reported neutralization assay results in addition to anti-SARS-CoV-2 antibody assays [34,37,41,48,51,55–79]. Thirty-one studies provided data on cellular immunity [17,21,22,34,37,41,45,46,55–67,72,74–77,79–84].

Immunogenicity data

Most studies (n = 157) reported immunogenicity data amounting to 25 209 participants, mainly cancer or haematological malignancy patients (7835, 31.1%), patients on dialysis (6302, 25.0%), solid organ transplant recipients (5974, 23.7%) and immune-mediated disease patients (4680, 18.6%). Eighty-three of those studies included a control population who also received the vaccine or recovering COVID-19 patients.

Cancer and haematological malignancy patients

Forty-three studies reported immunogenicity in patients with haematological malignancy (n = 6259, 79.9%) and cancer (n = 1480, 18.9%) (Table S3) [30,33,35,42,43,49,52,59,60,70,71,76], [83–113]. Twenty-three of these studies included a control population (overall n = 1931) [30,33,42,43,60,71,76,85–89,91,92,96,98,104,106–108,110–112] in which all but 15 participants developed post-vaccine antibodies [43,76,88,106,110,112]. Non-response rates among cancer and haematological malignancy populations ranged from 2% to 61% [30,89,90].

Malignancy-specific treatments were repeatedly associated with non-responder status, whether taken as a whole or specific treatments such as cytotoxic chemotherapy, Bruton tyrosine kinase inhibitors, anti-CD20 treatment or daratumumab-based regimens [30,33,35,42,43,70,71,76,83,85,86,89–92,95,100,102–106,110,112,113] (Table S3).

Patients with haematological malignancy

Non-response rates in patients with haematological malignancy ranged from 14% to 61% [89,101] (Fig. 2A). Patients with chronic lymphocytic leukaemia seemed at high risk of non-response with rates ranging from 28% to 77% [43,70,83,86,89,93,95,103,107,109]. Patients with multiple myeloma were at lower risk of non-response: rates ranged from 5% to 34% [86,88,92–94,103,104,108]. Patients with myeloproliferative neoplasms (chronic myeloid leukaemia and Philadelphia-negative myeloproliferative neoplasms) displayed lower rates of non-response, ranging from 12% to 20% [86,92,101,113]. In patients with lymphoma, non-response rates ranged from 30% to 58%, with the highest rate reported by Ghione et al. [33] in patients largely recently treated (52/86) with B-cell depleting treatment [83,86,93,94,100,107]. Patients with haematopoietic stem cell transplantation (HSCT) displayed non-response rates ranging from 14% to 31% in allogenic HSCT [35,84,102], and showed maintained response rates in Tzarfati et al. [86] (autologous HSCT) and antibody titres in Maneikis et al. [85] (allogenic and autologous HSCT), while they were at increased risk of non-response in Thakkar et al. [30] (mostly autologous HSCT). Only Dhakal et al. provided a non-response rate for patients with autologous HSCT which was estimated at 40% (18/45) [35].

Five studies provided results on cellular immunity, two using an enzyme-linked immunospot (ELISpot) assay [76,84], one with a Fluorospot assay [60] and one with an interferon-gamma release assay (IGRA) assay [83]. Non-response rates were usually higher in cellular than in antibody response [60,83,84] except in one study [76].

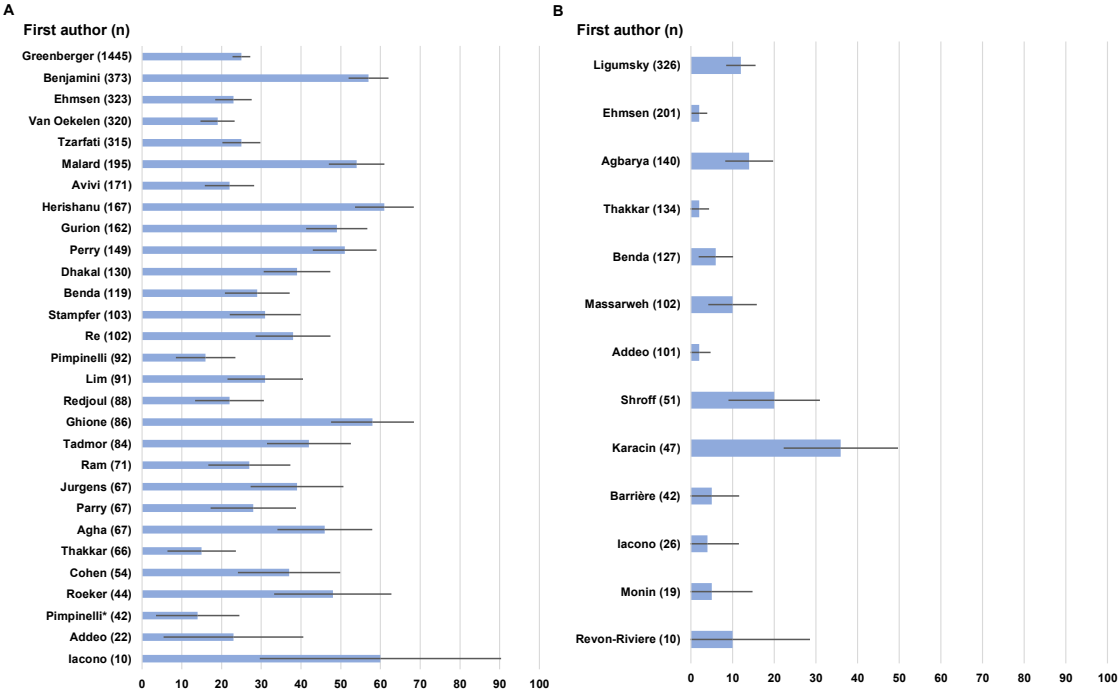

Fig. 2. Rates of non-response in patients with haematological malignancy (A) and cancer (B). Grey dashes represent the 95% CI. The studies are ordered by population size. Only studies with subgroup size $n \geq 10$ are represented.

Patients with cancer

Non-response rates in patients with cancer ranged from 2% to 36% [30,52,83,90] (Fig. 2B). Two large studies found some of the higher rates: Shroff et al. [59] (non-response rate 20%, 10/51) provided binary data on seroconversion only with a neutralization assay, and Karacin et al. [52] (non-response rate 36%, 17/47) included only patients undergoing active specific anti-cancer therapy which possibly contributed to an increased risk of non-response [52,59].

As did Shroff et al., Monin et al. tested for neutralizing antibodies: they found neutralizing antibodies against the wild type and the B.1.1.7 (alpha) variant spike protein in all participants who produced detectable post-vaccine anti-S IgG [59,60].

Both studies, along with Ehmsen et al., reported data on cellular immunity [59,60,83]. In patients without post-vaccine neutralizing antibodies, Shroff et al. found a non-response rate of 60% (6/10) with an ELISpot assay [59]. Non-response rates in Monin et al. were 13% (2/16) in patients with solid cancer and 25% (1/4) of patients with haematological malignancy with a Fluorospot assay [60]. As in patients with haematological malignancy, Ehmsen et al. found a higher non-response rate in cellular (tested via an IGRA assay) than in antibody response: 54% (109/201) vs 2% (4/201) respectively [83].

Patients on dialysis

Thirty-three studies reported immunogenicity in 6302 patients on dialysis (Table S4) [15–17,21,31,38,44,62–64,74,78,80,114–134]. Non-responder rates ranged from 2% to 30% (Fig. 3) [125,126]. Four studies were rated "good" in the risk of bias assessment: they all found low non-response rates ranging from 2% to 5% [21,125,130,133]. Simon et al. found a high non-response rate at 27% (22/80), at least partially explained by the choice of a higher cut-off (29 U/mL) than the one provided by the manufacturer of the serological assay [118,135]. Fifteen studies included a control group ($n = 779$ overall), in which all but nine participants developed post-vaccine antibodies [17,21,63,74,78,80,116,118,120,121,124,126,128,131,134]. Speer et al. performed neutralization assays which showed the same rate of non-response as the anti-S antibody assay: 3/17 (18%) [128]. In a further study, Speer et al. measured neutralizing antibodies in participants with seroconversion: all showed neutralizing antibodies against the B.1.1.7 strain (alpha variant), while only 15/24 had neutralizing antibodies against the B.1.351 strain (beta variant) [78]. Seven studies reported elements of cellular response, using either a flow cytometry technique [21,62,63,80], an ELISpot assay [64] or an IGRA assay [17,21,74]. Non-response rates were lower in T-cell response than antibody response in both Bertrand et al. and Sattler et al. [62,63]. Four studies found opposite results with higher non-response rates in cellular than in antibody response [17,21,64,74].

Treatment with immunosuppressive therapies was associated with non-responder status or lower antibody titres in several studies (Table S4) [62,64,129], as well as older age [17,31,117,118,121,122,124,133] or a lower lymphocyte count [64,124].

Solid organ transplant recipients

Forty-seven studies described immunogenicity across various solid organ transplant populations ($n = 5974$), mostly in kidney transplant recipients ($n = 3534$, 59.2%) (Table S5) [18,20–26,29,34,40,56–58], [62,63,65,66,69,72,73,75,77,79,81,120,126], [136–160]. Twenty-four of those studies included a control group representing overall 1399 participants [21,34,57,63,66,69,72,73,75,79,120,126,142–146,148,149,151,152,154–156], among whom only 12 did not mount a post-vaccine antibody immunity [21,69,145,155]. Non-responder rates ranged from 18% to 100% [40,149,152] (Fig. 4): 35–98% in kidney transplant recipients, 19–63% in liver transplant recipients, 25–88% in heart transplant recipients and 59–100% in lung transplant recipients (for studies with subgroup size n ≥ 10) (Fig. 5).

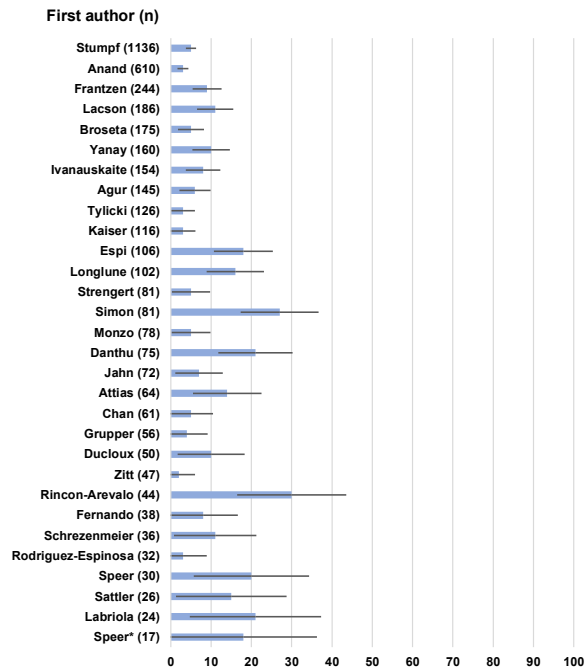

Fig. 3. Rates of non-response in patients on dialysis. We reported the latest endpoint within 30 days following vaccine completion if several endpoints were available. We reported the outcome following second dose in the studies reporting post-vaccine immunity following an additional dose. The studies are ordered by population size. Grey dashes represent the 95% CI. Only studies with subgroup size $n \geq 10$ are represented. *Speer et al. [128].

Eleven studies reported results of neutralization assays [34,63,66,69,72,77,79,126,145]. Non-response rates were close to those in anti-S assays in most studies [63,72,77,126], while several studies performed the assay only in anti-spike antibody positive participants who mostly tested positive in neutralization assays [69,79,145].

Fourteen studies included data on T-cell immunity, assessed through an ELISpot assay [56–58,62,65,75,81], flow cytometry [21,34,63,72,79] or an IGRA assay [21,66]. Most studies found lower non-response rates in cellular than in antibody response [56–58,62,63,72,79,81], while two studies found higher non-response rates in cellular than in antibody response [21,65].

Solid organ transplant-specific treatments (calcineurin inhibitors, antimetabolites, corticosteroids) were often associated with a higher non-response rate or lower antibody titres [20,21,24,40,56,62,65,69,72,75,81,136,138–142,144,145,148,154–157,159,160] (Table S5). Older age and lower estimated glomerular filtration rate were repeatedly associated with a non-responder status [21,24,79,120,138,142,144,155]. We found conflicting results regarding the impact of time since transplantation on vaccine response: seven studies found higher non-response rates or lower antibody titres in patients with recent transplantation, Rozen-Zvi et al. [138] found a longer time from transplantation was associated with lower antibody titres [21,62,79,139,141,143,155,160].

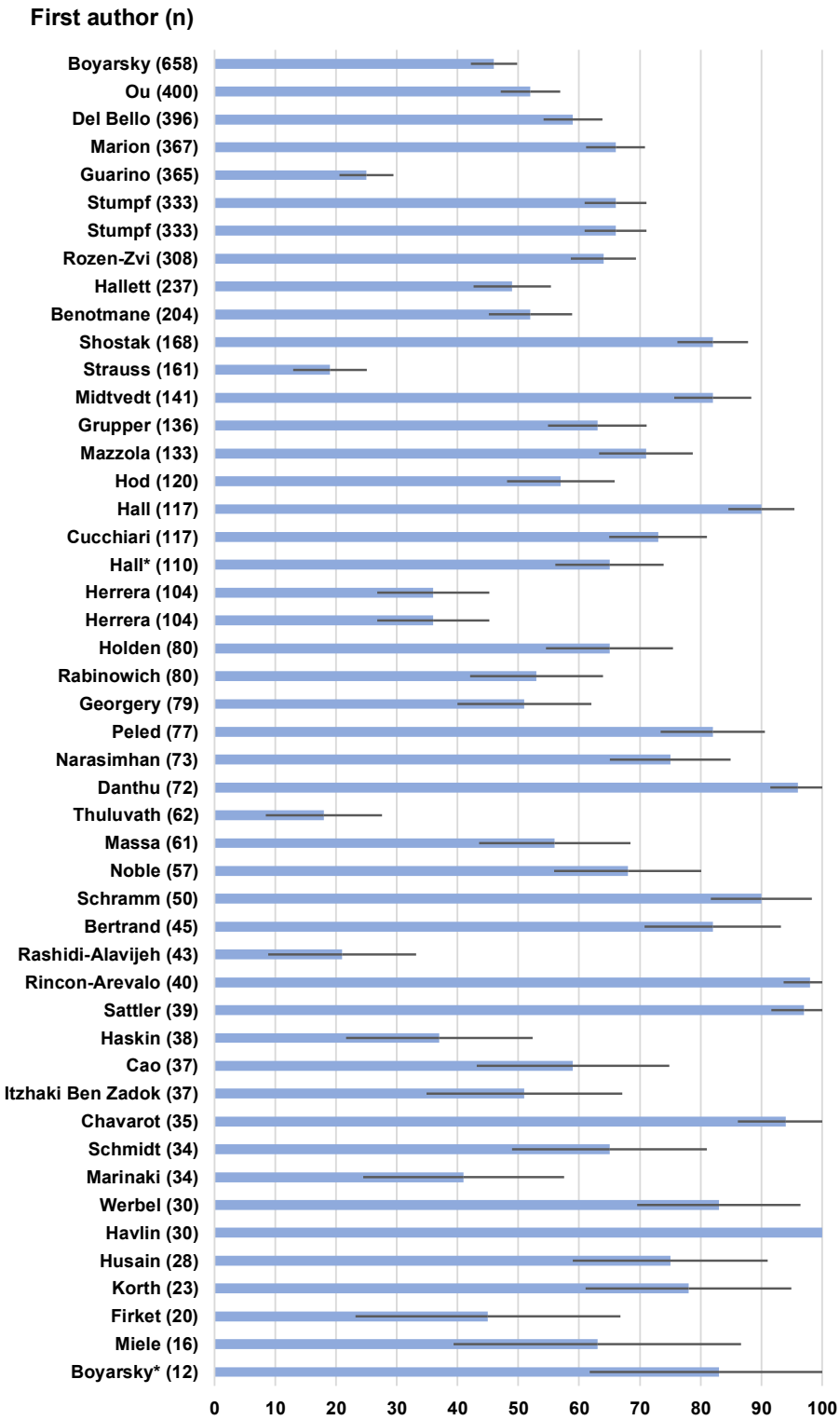

Fig. 4. Rates of non-response in solid organ transplant recipients. We reported the latest endpoint within 30 days following vaccine completion if several endpoints were available. We reported the outcome following second dose in the studies reporting post-vaccine immunity following an additional dose. Grey dashes represent the 95% CI. The studies are ordered by population size. *Hall et al. [72]. *Boyarsky et al. [29].

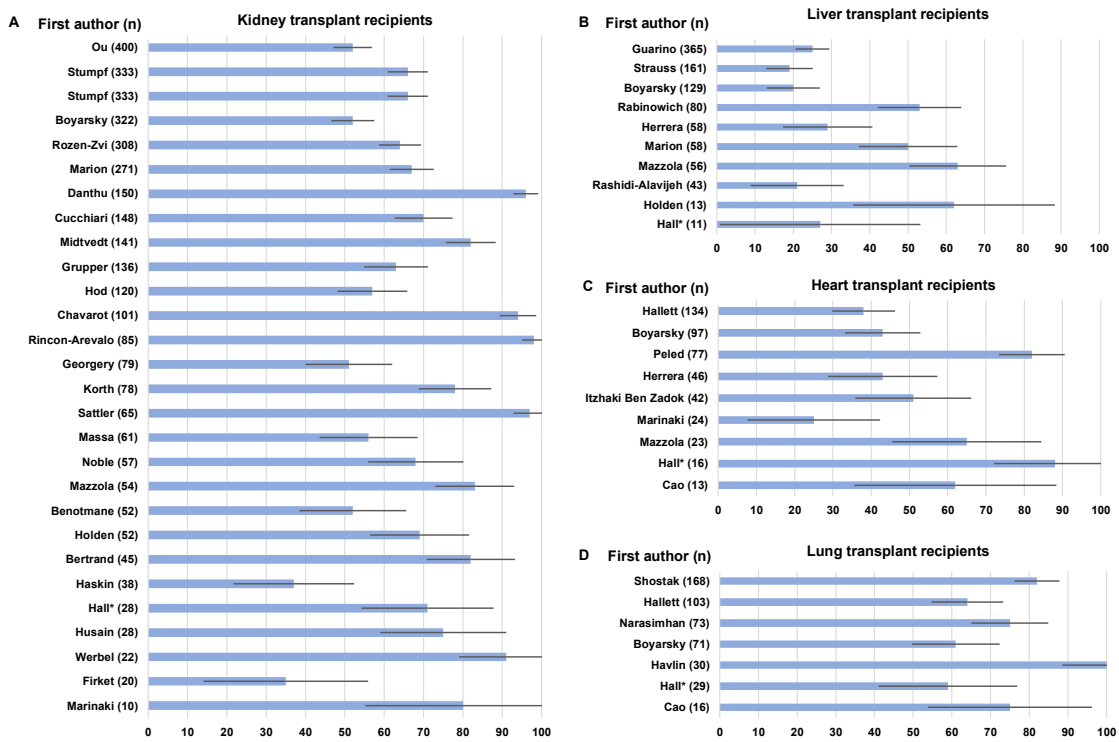

Fig. 5. Rates of non-response in solid organ transplant recipients: kidney (A), liver (B), heart (C) and lung (D). We reported the latest endpoint within 30 days following vaccine completion if several endpoints were available. We reported the outcome following second dose in the studies reporting post-vaccine immunity following an additional dose. Grey dashes represent the 95% CI. The studies are ordered by population size. Only studies with subgroup size $n \geq 10$ are represented. *Hall et al. [72].

Inflammatory immune-mediated diseases

Thirty-one studies reported immunogenicity in 4680 patients with inflammatory immune-mediated diseases (Table S6) [27,28,32,36,37,39,45–47,50,51,54,55,82,161–178]. Main represented groups included rheumatoid arthritis ($n = 665$), inflammatory bowel diseases ($n = 476$) and multiple sclerosis ($n = 231$). Twenty of those studies had a control group [32,37,45–47,50,51,55,161–164,166,167,169,171,172,174,177,178] ($n = 1609$), among which 16 participants failed to mount a post-vaccine antibody response [47,50,51,55,163,164].

Non-response rates ranged from 0% to 63% (Fig. 6) [36,39,55,168,171,172,177]. Among the studies with the highest non-response rates, Mrak et al. included only patients on rituximab, Connolly et al. [36] included 48 participants with ANCA-associated vasculitis, of whom 44 received rituximab, and Achiron et al. and Guerrieri et al. found high rates (respectively 47% and 50%) in patients with multiple sclerosis (MS) [164,168]. Six studies tested participants' sera with neutralization assays [32,37,51,163,172,174], one tested neutralization on a SARS-CoV-2 spike protein bearing the N501Y mutation (present in the alpha variant) [32]. Two studies provided non-response rates which were either the same as with anti-S IgG assay (0%, 0/26 [172]) or higher (44%, 375/859 vs. 29%, 245/859 with the anti-S assay [51]).

Six studies included elements of cellular response, using a flow cytometry technique [46,55], an ELISpot assay [37,45,178] or an IGRA assay [82]. Haberman et al. found activated CD8+ T-cells in all 24 participants who were not receiving methotrexate but in none of the 18 patients who were receiving methotrexate [55]. Prendecki et al. and Mrak et al. found lower non-response rates in cellular than in antibody response, while Benucci et al. found detectable T-cell response in four patients with no antibodies or low titres [45,82,178].

Specific treatments of the inflammatory disease negatively impacted post-vaccine response: B-cell depleting agents [28,50,161–165,169,175], methotrexate and other disease-modifying antirheumatic drugs (DMARDs) or corticosteroids [28,50,51,55,161–163,176]. When analysed, impact of TNF inhibitors varied across studies: while some found an association with a lower risk of non-response or no impact on response or antibody titres [28,46,161,163], two studies found they were associated with absence of seroconversion or low antibody titres [51,171].

Other immunosuppressed populations

Five studies conducted in people living with HIV found low non-response rates ranging from 0 to 4% [48,68,179] (among those, two studies were estimated of good quality in the risk of bias assessment [48,68]) or comparable antibody titres compared to an HIV-negative population [41,67].

Two studies by Hagin et al. and Abo-Helo et al. reported results of immunogenicity of the BNT162b2 vaccine in patients inborn errors of immunity (mostly common variable immunodeficiency): non-response rates were respectively 23% (6/26) and 27% (4/15) [61,180].

Lustig et al. reported immunogenicity data in 2607 healthcare workers who received BNT162b2, among whom 74 with an autoimmune disease and 12 with another immunosuppression were evaluated following the second dose [181]. Immunosuppression, but not autoimmune diseases, was associated with lower antibody titres. Kageyama et al. found a non-response rate of 4% (1/23) in healthcare workers who received corticosteroids [182].

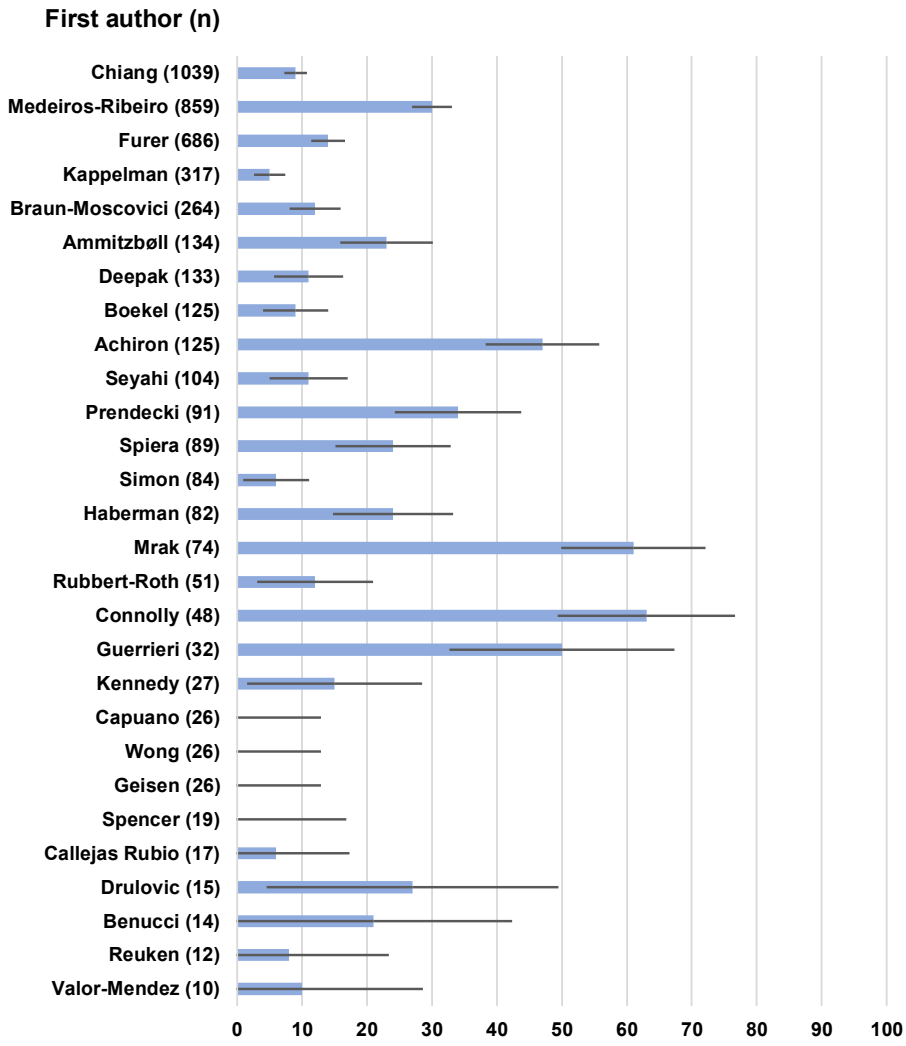

Fig. 6. Rates of non-response in patients with autoimmune inflammatory diseases. Grey dashes represent the 95% CI. The studies are ordered by population size.

Effect of an additional dose of vaccine

Ten studies reported the effect of an additional dose following a complete vaccination [16,19,22,23,25,26,75,77,129,153,157]. Seven were conducted in solid organ transplant recipients [22,23,25,26,75,77,153,157] (Table S5): non-response rates following the additional dose in the initially non-responders ranged from 51% to 68% [75,153]. Hall et al. conducted a randomized placebo-controlled trial (the only study rated "good" in the risk of bias assessment among those studying an additional dose), testing a third dose of the Moderna vaccine in 117 solid organ transplant recipients, and showed a lower non-response rate in the vaccine arm (45%, 27/60) than in the placebo arm (82%, 47/57) [77]. Alejo et al. continued the study by Werbel et al. and offered a fourth dose of vaccine to 18 patients of whom 50% (3/6) of the non-responders after the third dose showed positive antibody testing after the fourth dose [25,26]. Three studies were conducted in patients with end-stage renal disease [16,19,129]: non-response rates following the additional dose among the initially non-responders ranged from 50% to 60% (Table S4).

Effect of vaccine type

Immunogenicity varied across vaccine type: the Pfizer [21,38,39,103,130,159] and Janssen vaccines [38,39] were repeatedly associated with non-response status or lower antibody titres compared than the Moderna vaccine. Two studies found higher odds of non-response when vaccinated with the Janssen vaccine compared with the two mRNA vaccines [27,40].

Vaccine efficacy and effectiveness data

Five studies reported data in immunosuppressed populations [53,183–186]. A randomized controlled trial of the Novavax vaccine against the B.1.351 (beta) variant reported outcomes in a subgroup of 148 HIV-positive participants who were seronegative for SARS-CoV-2 at baseline. Efficacy could not be estimated in the group of people living with HIV: only six events occurred in this subgroup (four in the 76 participants in the vaccine group and two in the 72 participants in the placebo group) [53]. Nonetheless, vaccine efficacy estimates were lower when including participants living with

HIV (efficacy: 49.4%, 95% CI 6.1–72.8) than when analysis was restricted to HIV-negative participants (efficacy: 60.1%, 95% CI 19.9–80.1). Other phase 3 randomized controlled trials did not include immunosuppressed patients or did not provide subgroup analysis results [187–190]. Three observational retrospective studies estimated effectiveness on RT-PCR-proven SARS-CoV-2 infection in immunocompromised patients: a study in patients with inflammatory bowel diseases reported an 80.4% vaccine effectiveness of mRNA vaccines [184], an Israeli cohort included patients with immunosuppression (no further details) with a reported effectiveness of 71% (95% CI 37–87%), notably lower than across the entire study population (90%, 95% CI 79–95%) [183], and a study in solid organ transplant recipients found an incidence rate ratio of 0.19 (95% CI 0.049–0.503) [186]. One study evaluated effectiveness on COVID-19-related hospitalizations in a test-negative design and found an effectiveness of 62.9% (95% CI 20.8–82.6%) in an immunocompromised population (no further details), lower than across the non-immunocompromised population (91.3%, 95% CI 85.6–94.8%) [185].

Discussion

This review is the first to report available data on COVID 19 vaccination in different populations of immunocompromised patients. It highlights lower immunogenicity of COVID-19 vaccines in these patients than estimated in most previous clinical studies conducted in healthy volunteers [191–193]. Non-response rate varies widely and is higher in solid organ transplant recipients (especially lung and renal transplant recipients), patients with haematological malignancy (most of all patients with chronic lymphocytic leukaemia), and lower in patients with cancer, patients on dialysis and with varying levels across different immune-mediated diseases (seemingly higher in patients with MS), possibly due to differences in therapeutics. These variations are consistent with findings in other vaccines (influenza, pneumococcal and hepatitis B vaccines) among solid organ transplant recipients [194,195] and patients with haematological malignancies [196,197], while patients on dialysis often display satisfying immunogenicity [198] or higher than solid organ transplant recipients [199]. Only a few studies provided information on cellular immunity and neutralization assays. While some seemed to indicate a better cellular response than humoral antibody response [45,56–58,62,63,72,76,79,81], others found opposite results [17,21,60,64,65,74,76,83,84]. Lack of standardization of assays to detect T-cell immunity and various performances across different techniques (flow cytometry or ELISpot/fluorospot) may partly explain these discrepancies [200]. Further data on T-cell-mediated immunity are needed to determine to which extent post-vaccine immunity is compromised.

The majority of included studies involved mRNA-based vaccines. This is the consequence of the early availability of those vaccines, with data suggesting high immunogenicity in healthy volunteers and elderly, of particular interest in immunocompromised patients who are at high risk of severe COVID-19 [191]. As mRNA vaccines are being used for the first time, those are the first data we have on mRNA vaccines in immunocompromised populations. We only included studies on full vaccination schedules, thus data on ChAdOx1 nCoV-19 are still scarce, given the extended interval between the two doses implemented in some national vaccination campaigns [201]. Immunogenicity data suggesting higher immunogenicity of mRNA-based vaccines (especially the Moderna vaccine) than adenovirus-based vaccines warrant further investigation [27,30,38–40,170].

Risk factors for non-response status often included older age, which is consistent with data provided by phase 1 and 2 studies of COVID-19 vaccines [191,192], as well as in other vaccines such as influenza, pneumococcal and hepatitis B vaccines [202–205]. Immunosuppressive therapy and biological agents, especially B-cell depleting agents, often negatively impact immune responses to COVID-19 vaccines. These reports are consistent with immune response to other vaccines in populations receiving such treatments, mycophenolate [194] and anti-CD20 agents (in a rheumatological indication [206,207], haematological malignancy [208,209] or multiple sclerosis [210]), methotrexate [211], while TNF inhibitors variously affect immunogenicity [211,212].

This systematic review of literature highlights currently missing data. We identified only five articles on vaccine efficacy or effectiveness in immunosuppressed populations. Estimates of effectiveness appear lower than in the general population [183,213,214], which is consistent with the findings of this review regarding a diminished immunogenicity and reports of more breakthrough infections observed in these populations [215–217]. Data on variants of concern include the dedicated randomized controlled trial [53] and the study by Chodick et al. which took place during periods of high local prevalence of the alpha variant [183]. However, data on the delta variant are still missing, and studies in the general population suggest a reduced effectiveness against SARS-CoV-2 infection (but not against severe forms) with this variant [218,219]. No study has yet reported effectiveness nor efficacy of an additional dose of vaccine in immunocompromised populations. Further studies with longer follow-up will help determine long-term immunogenicity. Literature data are still scarce if existent in many immunocompromised populations, including patients with inborn errors of immunity, allogenic stem cell transplantation and people living with HIV. A search of the ClinicalTrials.gov database on 31 August 2021 revealed two ongoing randomized controlled trials in immunocompromised populations: one comparing the Moderna and Pfizer vaccines in solid organ transplant recipients and people living with HIV, and one in patients with chronic kidney disease and dialysis comparing the Moderna and Pfizer vaccines as third dose after two doses of mRNA vaccines. Other phase 2 or phase 3 studies evaluating currently not approved COVID-19 vaccines include people living with HIV.

This review has certain limitations. The included studies assessed post-vaccine antibody response through various anti-Spike protein assays, performed at different timepoints. Heterogeneity in populations and methods used to assess immunogenicity and frequent lack of details on included populations make it difficult to perform meta-analysis with currently available data, which is why we chose not to do so. Most included studies were observational with a small sample size, thus permitting little adjustment on confounding. We could not perform additional analyses of factors associated with non-response as individual data were mostly unavailable, thus we reported those as mentioned by the authors. Large studies with standardized assays allowing comparisons are needed [220]. Nonetheless, this review provides a comprehensive understanding of the current evidence to help decision-making regarding vaccination strategies in immunocompromised patients.

Targeted strategies might prove interesting in those populations, such as additional doses (currently recommended in France [12]), as suggested by some data presented in this review [16,24,26,129]. Other approaches such as heterologous vaccination [221,222], increased doses (as in hepatitis B vaccine [223,224]) might enhance immunogenicity, while prophylactic administration of monoclonal antibodies [225] or 'cocooning' vaccination of relatives and healthcare workers offer potential alternatives [226].

Overall, this systematic review highlights a diminished immunogenicity of COVID-19 vaccines, including mRNA-based vaccines, in immunocompromised populations, with varying levels across

different types of immunodepression. Alternative strategies are necessary to provide sufficient protection to these patients.

Transparency declaration

Dr Loubet reports personal fees from Pfizer, non-financial support from Sanofi Pasteur, non-financial support from Pfizer, personal fees from AstraZeneca, outside the submitted work. Dr Luong Nguyen reports personal fees from Pfizer, outside the submitted work. Other authors do not report any competing interests. Dr Wittkop reports grants and contracts from ANRS-MIE and Sidaction to the institution. Pr Launay reports grants and contracts from Pfizer, GSK, Janssen, Sanofi Pasteur, GSK, consulting fees from Pfizer, Janssen, Sanofi Pasteur, support for attending meetings and/or travel from Pfizer, Janssen, Sanofi Pasteur and participation on a data safety monitoring board or advisory board for Sanofi Pasteur and MSD, all unrelated to the submitted work.

Data availability

Extracted data are available almost entirely in the review (including supplementary information). Remaining data regarding the serological assays are available on request.

Author contributions

S.G., L.B.L.N., P.L. and O.L. designed the review. S.G. screened titles and abstract for eligibility. S.G. and L.B.L.N. independently assessed articles for inclusion. O.L. split the case in case of discrepancy. S.G. and L.B.L.N. independently assessed risk of bias of included studies. P.L. split the case in case of discrepancy. S.G. extracted data from the included studies. S.G. and L.B.L.N. jointly verified figures extracted from the studies. S.G., L.B.L.N., P.L. and O.L. drafted the first versions of the manuscript. E.T., X.d.L. and L.W. critically reviewed the manuscript. All authors received and approved the current version of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cmi.2021.09.036.

References

[1] Tian Y, Qiu X, Wang C, Zhao J, Jiang X, Niu W, et al. Cancer associates with risk and severe events of COVID-19: a systematic review and meta-analysis. Int J Cancer 2021;148:363–74.

[2] Raja MA, Mendoza MA, Villavicencio A, Anjan S, Reynolds JM, Kittipibul V, et al. COVID-19 in solid organ transplant recipients: a systematic review and meta-analysis of current literature. Transplant Rev Orlando Fla 2021;35:100588.

[3] Caillard S, Chavarot N, Francois H, Matignon M, Greze C, Kamar N, et al. Is COVID-19 infection more severe in kidney transplant recipients? Am J Transplant Surg 2021;21:1295–303.

[4] Couchoud C, Bayer F, Ayav C, Béchade C, Brunet P, Chantrel F, et al. Low incidence of SARS-CoV-2, risk factors of mortality and the course of illness in the French national cohort of dialysis patients. Kidney Int 2020;98:1519–29.

[5] Hilbrands LB, Duivenvoorden R, Vart P, Franssen CFM, Hemmelder MH, Jager KJ, et al. COVID-19-related mortality in kidney transplant and dialysis patients: results of the ERACODA collaboration. Nephrol Dial Transplant 2020;35:1973–83.

[6] FAI2R/SFR/SNFMI/SOFREMIP/CRI/IMIDIATE consortium and contributors. Severity of COVID-19 and survival in patients with rheumatic and inflammatory diseases: data from the French RMD COVID-19 cohort of 694 patients. Ann Rheum Dis 2020;80:527–38.

[7] Crespo M, Collado S, Mir M, Cao H, Barbosa F, Serra C, et al. Efficacy of influenza A H1N1/2009 vaccine in hemodialysis and kidney transplant patients. Clin J Am Soc Nephrol 2011;6:2208–14.

[8] Boey L, Curinckx A, Roelants M, Derdelinckx I, Van Wijngaerden E, De Munter P, et al. Immunogenicity and safety of the nine-valent human papillomavirus vaccine in solid organ transplant recipients and HIV-infected adults. Clin Infect Dis Off Publ Infect Dis Soc Am 2021;73:e661–71. https://doi.org/10.1093/cid/ciaa1897.

[9] Blanchette PS, Chung H, Pritchard KI, Earle CC, Campitelli MA, Buchan SA, et al. Influenza vaccine effectiveness among patients with cancer: a population-based study using health administrative and laboratory testing Data from Ontario, Canada. J Clin Oncol 2019;37:2795–804.

[10] Nakashima K, Aoshima M, Ohfuji S, Suzuki K, Katsurada M, Katsurada N, et al. Immunogenicity of trivalent influenza vaccine in patients with lung cancer undergoing anticancer chemotherapy. Hum Vaccine Immunother 2017;13:543–50.

[11] Rondaan C, Furer V, Heijstek MW, Agmon-Levin N, Bijl M, Breedveld FC, et al. Efficacy, immunogenicity and safety of vaccination in adult patients with autoimmune inflammatory rheumatic diseases: a systematic literature review for the 2019 update of EULAR recommendations. RMD Open 2019;5:e001035.

[12] Direction Générale de la Santé. DGS Precisions sur la vaccination IMD. n.d. https://solidarites-sante.gouv.fr/IMG/pdf/dgs_urgent_52_precisions_sur_la_vaccination_imd.pdf. [Accessed 2 July 2021]. accessed

[13] Commissioner O of the. Coronavirus (COVID-19) Update: FDA Authorizes Additional Vaccine Dose for Certain Immunocompromised Individuals. FDA 2021, https://www.fda.gov/news-events/press-announcements/coronavirus-covid-19-update-fda-authorizes-additional-vaccine-dose-certain-immunocompromised. [Accessed 31 August 2021]. accessed.

[14] National Institutes of Health. Study quality assessment tools | NHLBI, NIH. n.d. https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools. [Accessed 2 July 2021]. accessed

[15] Ducloux D, Colladant M, Chabannes M, Yannaraki M, Courivaud C. Humoral response after BNT162b2 mRNA COVID-19 vaccination in patients on haemodialysis depends on immune status. Clin Kidney J 2021;14:2266–7.

[16] Ducloux D, Colladant M, Chabannes M, Yannaraki M, Courivaud C. Humoral response after 3 doses of the BNT162b2 mRNA COVID-19 vaccine in patients on hemodialysis. Kidney Int 2021;100:702–4.

[17] Espi M, Charmetant X, Barba T, Koppe L, Pelletier C, Kalbacher E, et al. The ROMANOV study found impaired humoral and cellular immune responses to SARS-CoV-2 mRNA vaccine in virus-unexposed patients receiving maintenance hemodialysis. Kidney Int 2021;100:928–36.

[18] Boyarsky BJ, Chiang TP-Y, Teles AT, Greenberg RS, Krach MR, Ou MT, et al. Antibody kinetics and durability in SARS-CoV-2 mRNA vaccinated solid organ transplant recipients. Transplantation 2021;105:e137–8.

[19] Espi M, Charmetant X, Barba T, Pelletier C, Koppe L, Chalencon E, et al. Justification, safety, and efficacy of a third dose of mRNA vaccine in maintenance hemodialysis patients: a prospective observational study. MedRxiv 2021. https://doi.org/10.1101/2021.07.02.21259913.

[20] Boyarsky BJ, Werbel WA, Avery RK, Tobian AAR, Massie AB, Segev DL, et al. Antibody response to 2-dose SARS-COV-2 mRNA vaccine series in solid organ transplant recipients. JAMA - J Am Med Assoc 2021;325:2204–6.

[21] Stumpf J, Siepmann T, Lindner T, Karger C, Schwöbel J, Anders L, et al. Humoral and cellular immunity to SARS-CoV-2 vaccination in renal transplant versus dialysis patients: a prospective, multicenter observational study using mRNA-1273 or BNT162b2 mRNA vaccine. Lancet Reg Health Eur 2021;9:100178.

[22] Stumpf J, Tonnus W, Paliege A, Rettig R, Steglich A, Gembardt F, et al. Cellular and humoral immune responses after three doses of BNT162b2 mRNA SARS-Cov-2 vaccine in kidney transplant. Transplantation 2021. https://doi.org/10.1097/tp.0000000000003903. Ahead of print.

[23] Del Bello A, Abravanel F, Marion O, Couat C, Esposito L, Lavayssière L, et al. Efficiency of a boost with a third dose of anti-SARS-CoV-2 messenger RNA-based vaccines in solid organ transplant recipients. Am J Transplant 2021. https://doi.org/10.1111/ajt.16775.

[24] Kamar N, Abravanel F, Marion O, Couat C, Izopet J, Del Bello A. Three Doses of an mRNA Covid-19 vaccine in solid-organ transplant recipients. N Engl J Med 2021;385:661–2.

[25] Alejo JL, Mitchell J, Chiang TP-Y, Abedon AT, Boyarsky BJ, Avery RK, et al. Antibody response to a fourth dose of a SARS-CoV-2 vaccine in solid organ transplant recipients: a case series. Transplantation 2021. https://doi.org/10.1097/TP.0000000000003934. Ahead of print.

[26] Werbel WA, Boyarsky BJ, Ou MT, Massie AB, Tobian AAR, Garonzik-Wang JM, et al. Safety and immunogenicity of a third dose of SARS-CoV-2 vaccine in solid organ transplant recipients: a case series. Ann Intern Med 2021;174:1330–2.

[27] Chiang TP-Y, Connolly CM, Ruddy JA, Boyarsky BJ, Alejo JL, Werbel WA, et al. Antibody response to the Janssen/Johnson & Johnson SARS-CoV-2 vaccine in patients with rheumatic and musculoskeletal diseases. Ann Rheum Dis 2021;80:1365–6.

[28] Ruddy JA, Connolly CM, Boyarsky BJ, Werbel WA, Christopher-Stine L, Garonzik-Wang J, et al. High antibody response to two-dose SARS-CoV-2 messenger RNA vaccination in patients with rheumatic and musculoskeletal diseases. Ann Rheum Dis 2021;80:1351–2.

[29] Boyarsky BJ, Chiang TP-Y, Ou MT, Werbel WA, Massie AB, Segev DL, et al. Antibody response to the Janssen COVID-19 vaccine in solid organ transplant recipients. Transplantation 2021;105:e82–3.

[30] Thakkar A, Gonzalez-Lugo JD, Goradia N, Gali R, Shapiro LC, Pradhan K, et al. Seroconversion rates following COVID-19 vaccination among patients with cancer. Cancer Cell 2021;39:1081–90.

[31] Anand S, Montez-Rath M, Han J, Garcia P, Cadden L, Hunsader P, et al. Antibody response to COVID-19 vaccination in patients receiving dialysis. J Am Soc Nephrol JASN 2021;32:2435–8.
[32] Dailey J, Kozhaya L, Dogan M, Hopkins D, Lapin B, Herbst K, et al. Antibody responses to SARS-CoV-2 after infection or vaccination in children and young adults with inflammatory bowel disease. MedRxiv 2021. https://doi.org/10.1101/2021.06.12.21258810.
[33] Ghione P, Gu JJ, Attwood K, Torka P, Goel S, Sundaram S, et al. Impaired humoral responses to COVID-19 vaccination in patients with lymphoma receiving B-cell directed therapies. Blood 2021;138:811–4.
[34] Lemieux JE, Li A, Gentili M, Perugino CA, Weiss ZF, Bowman K, et al. Vaccine serologic responses among transplant patients associate with COVID-19 infection and T peripheral helper cells. MedRxiv 2021. https://doi.org/10.1101/2021.07.11.21260338.
[35] Dhakal B, Abedin SM, Fenske TS, Chhabra S, Ledeboer N, Hari P, et al. Response to SARS-CoV-2 vaccination in patients after hematopoietic cell transplantation and CAR-T cell therapy. Blood 2021;138:1278–81.
[36] Connolly CM, Koenig D, Ravi SN, Azar A, Kant S, Dalal M, et al. Correspondence on "SARS-CoV-2 vaccination in rituximab-treated patients: evidence for impaired humoral but inducible cellular immune response" by Bonelli *et al.* Ann Rheum Dis 2021;80:e164. https://doi.org/10.1136/annrheumdis-2021-220972.
[37] Izmirly PM, Kim MY, Samanovic M, Fernandez-Ruiz R, Ohana S, Deonaraine KK, et al. Evaluation of immune response and disease status in SLE patients following SARS-CoV-2 vaccination. Arthritis Rheumatol 2021. https://doi.org/10.1002/art.41937.
[38] Garcia P, Anand S, Han J, Montez-Rath M, Sun S, Shang T, et al. COVID19 vaccine type and humoral immune response in patients receiving dialysis. MedRxiv Preprint Serv Health Sci 2021. https://doi.org/10.1101/2021.08.02.21261516.
[39] Spencer EA, Klang E, Dolinger M, Pittman N, Dubinsky MC. Seroconversion following SARS-CoV-2 infection or vaccination in pediatric IBD patients. Inflamm Bowel Dis 2021. https://doi.org/10.1093/ibd/izab194.
[40] Thuluvath PJ, Robarts P, Chauhan M. Analysis of antibody responses after COVID-19 vaccination in liver transplant recipients and those with chronic liver diseases. J Hepatol 2021. https://doi.org/10.1016/j.jhep.2021.08.008.
[41] Frater J, Ewer KJ, Ogbe A, Pace M, Adele S, Adland E, et al. Safety and immunogenicity of the ChAdOx1 nCoV-19 (AZD1222) vaccine against SARS-CoV-2 in HIV infection: a single-arm substudy of a phase 2/3 clinical trial. Lancet HIV 2021;8:e474–85. https://doi.org/10.1016/S2352-3018(21)00103-X.
[42] Lim SH, Campbell N, Johnson M, Joseph-Pietras D, Collins GP, O'Callaghan A, et al. Antibody responses after SARS-CoV-2 vaccination in patients with lymphoma. Lancet Haematol 2021;8:e542–4.
[43] Parry H, McIlroy G, Bruton R, Ali M, Stephens C, Damery S, et al. Antibody responses after first and second Covid-19 vaccination in patients with chronic lymphocytic leukaemia. Blood Cancer J 2021;11:136.
[44] Fernando E, Govindan S. Neutralizing SARS-CoV-2 antibody response and protective effect of two doses of ChAdOx1 nCoV-19 and BBV152 vaccines in hemodialysis patients – preliminary report. Kidney Int Rep 2021;6:2521–2.
[45] Prendecki M, Clarke C, Edwards H, McIntyre S, Mortimer P, Gleeson S, et al. Humoral and T-cell responses to SARS-CoV-2 vaccination in patients receiving immunosuppression. Ann Rheum Dis 2021;80:1322–9. https://doi.org/10.1136/annrheumdis-2021-220626.
[46] Reuken PA, Andreas N, Grunert PC, Glöckner S, Kamradt T, Stallmach A. T cell response after SARS-CoV-2 vaccination in immunocompromised patients with inflammatory bowel disease. J Crohns Colitis 2021. https://doi.org/10.1093/ecco-jcc/jjab147.
[47] Boekel L, Steenhuis M, Hooijberg F, Besten YR, van Kempen ZLE, Kummer LY, et al. Antibody development after COVID-19 vaccination in patients with autoimmune diseases in the Netherlands: a substudy of data from two prospective cohort studies. Lancet Rheumatol 2021. https://doi.org/10.1016/S26659913(21)002228.
[48] Madhi SA, Koen AL, Izu A, Fairlie L, Cutland CL, Baillie V, et al. Safety and immunogenicity of the ChAdOx1 nCoV-19 (AZD1222) vaccine against SARS-CoV-2 in people living with and without HIV in South Africa: an interim analysis of a randomised, double-blind, placebo-controlled, phase 1B/2A trial. Lancet HIV 2021;8:E568–80.
[49] Heudel P, Favier B, Assaad S, Zrounba P, Blay J-Y. Reduced SARS-CoV-2 infection and death after two doses of COVID-19 vaccines in a series of 1503 cancer patients. Ann Oncol Off J Eur Soc Med Oncol 2021:2210–9. https://doi.org/10.1016/j.annonc.2021.07.012.
[50] Seyahi E, Bakhdiyarli G, Oztas M, Kuskucu MA, Tok Y, Sut N, et al. Antibody response to inactivated COVID-19 vaccine (CoronaVac) in immune-mediated diseases: a controlled study among hospital workers and elderly. Rheumatol Int 2021;41:1429–40.
[51] Medeiros-Ribeiro AC, Aikawa NE, Saad CGS, Yuki EFN, Pedrosa T, Fusco SRG, et al. Immunogenicity and safety of the CoronaVac inactivated vaccine in patients with autoimmune rheumatic diseases: a phase 4 trial. Nat Med 2021;27:1744–51. https://doi.org/10.1038/s41591-021-01469-5.
[52] Karacin C, Eren T, Zeynelgil E, Imamoglu GI, Altinbas M, Karadag I, et al. Immunogenicity and safety of the CoronaVac vaccine in patients with cancer receiving active systemic therapy. Future Oncol Lond Engl 2021. https://doi.org/10.2217/fon-2021-0597.
[53] Shinde V, Bhikha S, Hoosain Z, Archary M, Bhorat Q, Fairlie L, et al. Efficacy of NVX-CoV2373 Covid-19 vaccine against the B.1.351 variant. N Engl J Med 2021;384:1899–909.
[54] Drulovic J, Ivanovic J, Martinovic V, Tamas O, Veselinovic N, Cujic D, et al. Humoral response to SARS-CoV-2 and COVID-19 vaccines in patients with multiple sclerosis treated with immune reconstitution therapies. Mult Scler Relat Disord 2021;54:103150.
[55] Haberman RH, Herati RS, Simon D, Samanovic M, Blank RB, Tuen M, et al. Methotrexate hampers immunogenicity to BNT162B2 mRNA covid-19 vaccine in immune-mediated inflammatory disease. Ann Rheum Dis 2020;80:1339–44. https://doi.org/10.1136/annrheumdis-2021-220597.
[56] Cucchiari D, Egri N, Bodro M, Herrera S, Del Risco-Zevallos J, Casals-Urquiza J, et al. Cellular and humoral response after mRNA-1273 SARS-CoV-2 vaccine in kidney transplant recipients. Am J Transplant 2021;21:2727–39.
[57] Miele M, Busà R, Russelli G, Sorrentino MC, Di Bella M, Timoneri F, et al. Impaired anti-SARS-CoV-2 humoral and cellular immune response induced by Pfizer-BioNTech BNT162b2 mRNA vaccine in solid organ transplanted patients. Am J Transplant 2021;21:2919–21.
[58] Chavarot N, Ouedrani A, Marion O, Leruez-Ville M, Villain E, Baaziz M, et al. Poor Anti-SARS-CoV-2 humoral and T-cell responses after 2 injections of mRNA vaccine in kidney transplant recipients treated with belatacept. Transplantation 2021;105:e94–5.
[59] Shroff RT, Chalasani P, Wei R, Pennington D, Quirk G, Schoenle MV, et al. Immune responses to COVID-19 mRNA vaccines in patients with solid tumors on active, immunosuppressive cancer therapy. MedRxiv Preprint Serv Health Sci 2021. https://doi.org/10.1101/2021.05.13.21257129.
[60] Monin L, Laing AG, Muñoz-Ruiz M, McKenzie DR, del Molino del Barrio I, Alaguthurai T, et al. Safety and immunogenicity of one versus two doses of the COVID-19 vaccine BNT162b2 for patients with cancer: interim analysis of a prospective observational study. Lancet Oncol 2021;22:765–78.
[61] Hagin D, Freund T, Navon M, Halperin T, Adir D, Marom R, et al. Immunogenicity of Pfizer-BioNTech COVID-19 vaccine in patients with inborn errors of immunity. J Allergy Clin Immunol 2021;148:739–49.
[62] Bertrand D, Hamzaoui M, Lemée V, Lamulle J, Hanoy M, Laurent C, et al. Antibody and T cell response to SARS-CoV-2 messenger RNA BNT162b2 vaccine in kidney transplant recipients and hemodialysis patients. J Am Soc Nephrol 2021;32:2147–52.
[63] Sattler A, Schrezenmeier E, Weber UA, Potekhin A, Bachmann F, Straub-Hohenbleicher H, et al. Impaired humoral and cellular immunity after SARS-CoV2 BNT162b2 (Tozinameran) prime-boost vaccination in kidney transplant recipients. J Clin Invest 2021;131:e.150175.
[64] Broseta JJ, Rodríguez-Espinosa D, Rodríguez N, Mosquera MDM, Marcos MÁ, Egri N, et al. Humoral and cellular responses to mRNA-1273 and BNT162b2 SARS-CoV-2 vaccines administered to hemodialysis patients. Am J Kidney Dis 2021;78:571–81.
[65] Holden IK, Bistrup C, Nilsson AC, Hansen JF, Abazi R, Davidsen JR, et al. Immunogenicity of SARS-CoV-2 mRNA vaccine in solid organ transplant recipients. J Intern Med 2021. https://doi.org/10.1111/joim.13361.
[66] Schramm R, Costard-Jäckle A, Rivinius R, Fischer B, Müller B, Boeken U, et al. Poor humoral and T-cell response to two-dose SARS-CoV-2 messenger RNA vaccine BNT162b2 in cardiothoracic transplant recipients. Clin Res Cardiol 2021;110:1142–9.
[67] Woldemeskel BA, Karaba AH, Garliss CC, Beck EJ, Wang KH, Laeyendecker O, et al. The BNT162b2 mRNA vaccine elicits robust humoral and cellular immune responses in people living with HIV. Clin Infect Dis 2021. https://doi.org/10.1093/cid/ciab648.
[68] Levy I, Wieder-Finesod A, Litchevsky V, Biber A, Indenbaum V, Olmer L, et al. Immunogenicity and safety of the BNT162b2 mRNA Covid-19 vaccine in people living with HIV-1. Clin Microbiol Infect 2021:423–7. https://doi.org/10.1016/j.cmi.2021.07.031.
[69] Hod T, Ben-David A, Olmer L, Levy I, Ghinea R, Mor E, et al. Humoral response of renal transplant recipients to the BNT162b2 SARS-CoV-2 mRNA vaccine using both RBD IgG and neutralizing antibodies. Transplantation 2021. https://doi.org/10.1097/TP.0000000000003889.
[70] Benjamini O, Rokach L, Itchaki G, Braester A, Shvidel L, Goldschmidt N, et al. Safety and efficacy of BNT162b mRNA Covid19 vaccine in patients with chronic lymphocytic leukemia. Haematologica 2021. https://doi.org/10.3324/haematol.2021.279196.
[71] Terpos E, Gavriatopoulou M, Ntanasis-Stathopoulos I, Briasoulis A, Gumeni S, Malandrakis P, et al. The neutralizing antibody response post COVID-19 vaccination in patients with myeloma is highly dependent on the type of anti-myeloma treatment. Blood Cancer J 2021;11:138.
[72] Hall VG, Ferreira VH, Ierullo M, Ku T, Marinelli T, Majchrzak-Kita B, et al. Humoral and cellular immune response and safety of two-dose SARS-CoV-2 mRNA-1273 vaccine in solid organ transplant recipients. Am J Transplant 2021. https://doi.org/10.1111/ajt.16766.
[73] Cao J, Liu X, Muthukumar A, Gagan J, Jones P, Zu Y. Poor humoral response in solid organ transplant recipients following complete mRNA SARS-CoV-2 vaccination. Clin Chem 2021. https://doi.org/10.1093/clinchem/hvab149.
[74] Strengert M, Becker M, Ramos GM, Dulovic A, Gruber J, Juengling J, et al. Cellular and humoral immunogenicity of a SARS-CoV-2 mRNA vaccine in patients on haemodialysis. EBioMedicine 2021;70:103524.
[75] Massa F, Cremoni M, Gerard A, Grabsi H, Rogier L, Blois M, et al. Safety and cross-variant immunogenicity of a three-dose COVID-19 mRNA vaccine

regimen in kidney transplant recipients. Rochester, NY: Social Science Research Network; 2021. https://doi.org/10.2139/ssrn.3890865.
[76] Malard F, Gaugler B, Gozlan J, Bouquet L, Fofana D, Siblany L, et al. Weak immunogenicity of SARS-CoV-2 vaccine in patients with hematologic malignancies. Blood Cancer J 2021;11:142.
[77] Hall VG, Ferreira VH, Ku T, Ierullo M, Majchrzak-Kita B, Chaparro C, et al. Randomized trial of a third dose of mRNA-1273 vaccine in transplant recipients. N Engl J Med 2021;385:144–6.
[78] Speer C, Benning L, Töllner M, Nusshag C, Kälble F, Reichel P, et al. Neutralizing antibody response against variants of concern after vaccination of dialysis patients with BNT162b2. Kidney Int 2021;100:700–2.
[79] Schmidt T, Klemis V, Schub D, Schneitler S, Reichert MC, Wilkens H, et al. Cellular immunity predominates over humoral immunity after homologous and heterologous mRNA and vector-based COVID-19 vaccine regimens in solid organ transplant recipients. Am J Transplant 2021. https://doi.org/10.1111/ajt.16818.
[80] Blazquez-Navarro A, Safi L, Meister TL, Thieme CJ, Kaliszczyk S, Paniskaki K, et al. Superior cellular and humoral immunity toward SARS-CoV-2 reference and alpha and beta VOC strains in COVID-19 convalescent as compared to the prime boost BNT162b2-vaccinated dialysis patients. Kidney Int 2021;100:698–700.
[81] Herrera S, Colmenero J, Pascal M, Escobedo M, Castel MA, Sole-González E, et al. Cellular and humoral immune response after mRNA-1273 SARS-CoV-2 vaccine in liver and heart transplant recipients. Am J Transplant 2021. https://doi.org/10.1111/ajt.16768.
[82] Benucci M, Damiani A, Infantino M, Manfredi M, Grossi V, Lari B, et al. Presence of specific T cell response after SARS-CoV-2 vaccination in rheumatoid arthritis patients receiving rituximab. Immunol Res 2021;69:309–11.
[83] Ehmsen S, Asmussen A, Jeppesen SS, Nilsson AC, Østerlev S, Vestergaard H, et al. Antibody and T cell immune responses following mRNA COVID-19 vaccination in patients with cancer. Cancer Cell 2021;39:1034–6.
[84] Ram R, Hagin D, Kikozashvilli N, Freund T, Amit O, Bar-On Y, et al. Safety and immunogenicity of the BNT162b2 mRNA COVID-19 vaccine in patients after allogeneic HCT or CD19-based CART therapy-A single-center prospective cohort study. Transplant Cell Ther 2021;27:788–94.
[85] Maneikis K, Šablauskas K, Ringelevičiūtė U, Vaitekėnaitė V, Čekauskienė R, Kryžauskaitė L, et al. Immunogenicity of the BNT162b2 COVID-19 mRNA vaccine and early clinical outcomes in patients with haematological malignancies in Lithuania: a national prospective cohort study. Lancet Haematol 2021;8:e583–92.
[86] Tzarfati KH, Gutwein O, Apel A, Rahimi-Levene N, Sadovnik M, Harel L, et al. BNT162b2 COVID-19 vaccine is significantly less effective in patients with hematologic malignancies. Am J Hematol 2021;96:1195–203.
[87] Fong D, Mair MJ, Mitterer M. High levels of anti-SARS-CoV-2 IgG antibodies in previously infected patients with cancer after a single dose of BNT 162b2 vaccine. Eur J Cancer Oxf Engl 2021;154:4–6.
[88] Avivi I, Balaban R, Shragai T, Sheffer G, Morales M, Aharon A, et al. Humoral response rate and predictors of response to BNT162b2 mRNA COVID19 vaccine in patients with multiple myeloma. Br J Haematol 2021;195:186–93.
[89] Herishanu Y, Avivi I, Aharon A, Shefer G, Levi S, Bronstein Y, et al. Efficacy of the BNT162b2 mRNA COVID-19 vaccine in patients with chronic lymphocytic leukemia. Blood 2021;137:3165–73.
[90] Addeo A, Shah PK, Bordry N, Hudson RD, Albracht B, Di Marco M, et al. Immunogenicity of SARS-CoV-2 messenger RNA vaccines in patients with cancer. Cancer Cell 2021;39:1091–8. e2.
[91] Massarweh A, Eliakim-Raz N, Stemmer A, Levy-Barda A, Yust-Katz S, Zer A, et al. Evaluation of seropositivity following BNT162b2 messenger RNA vaccination for SARS-CoV-2 in patients undergoing treatment for cancer. JAMA Oncol 2021;7:1133–40.
[92] Pimpinelli F, Marchesi F, Piaggio G, Giannarelli D, Papa E, Falcucci P, et al. Fifth-week immunogenicity and safety of anti-SARS-CoV-2 BNT162b2 vaccine in patients with multiple myeloma and myeloproliferative malignancies on active treatment: preliminary data from a single institution. J Hematol Oncol 2021;14:81.
[93] Agha M, Blake M, Chilleo C, Wells A, Haidar G. Suboptimal response to COVID-19 mRNA vaccines in hematologic malignancies patients. MedRxiv Preprint Serv Health Sci 2021. https://doi.org/10.1101/2021.04.06.21254949.
[94] Cohen D, Hazut Krauthammer S, Cohen YC, Perry C, Avivi I, Herishanu Y, et al. Correlation between BNT162b2 mRNA Covid-19 vaccine-associated hypermetabolic lymphadenopathy and humoral immunity in patients with hematologic malignancy. Eur J Nucl Med Mol Imag 2021;48:3540–9.
[95] Roeker LE, Knorr DA, Pessin MS, Ramanathan LV, Thompson MC, Leslie LA, et al. Anti-SARS-CoV-2 antibody response in patients with chronic lymphocytic leukemia. Leukemia 2020;34:3047–9.
[96] Barrière J, Chamorey E, Adjtoutah Z, Castelnau O, Mahamat A, Marco S, et al. Impaired immunogenicity of BNT162b2 anti-SARS-CoV-2 vaccine in patients treated for solid tumors. Ann Oncol 2021;32:1053–5.
[97] Iacono D, Cerbone L, Palombi L, Cavalieri E, Sperduti I, Cocchiara RA, et al. Serological response to COVID-19 vaccination in patients with cancer older than 80 years. J Geriatr Oncol 2021:136–43. https://doi.org/10.1016/j.jgo.2021.06.002.
[98] Diefenbach C, Caro J, Koide A, Grossbard M, Goldberg JD, Raphael B, et al. Impaired humoral immunity to SARS-CoV-2 vaccination in non-Hodgkin lymphoma and CLL patients. MedRxiv 2021. https://doi.org/10.1101/2021.06.02.21257804.
[99] Revon-Riviere G, Ninove L, Min V, Rome A, Coze C, Verschuur A, et al. The BNT162b2 mRNA COVID-19 vaccine in adolescents and young adults with cancer: a monocentric experience. Eur J Cancer Oxf Engl 2021;154:30–4.
[100] Gurion R, Rozovski U, Itchaki G, Gafter-Gvili A, Leibovitch C, Raanani P, et al. Humoral serologic response to the BNT162b2 vaccine is abrogated in lymphoma patients within the first 12 months following treatment with anti-CD2O antibodies. Haematologica 2021. https://doi.org/10.3324/haematol.2021.279216.
[101] Pimpinelli F, Marchesi F, Piaggio G, Giannarelli D, Papa E, Falcucci P, et al. Lower response to BNT162b2 vaccine in patients with myelofibrosis compared to polycythemia vera and essential thrombocythemia. J Hematol Oncol 2021;14:119.
[102] Redjoul R, Le Bouter A, Beckerich F, Fourati S, Maury S. Antibody response after second BNT162b2 dose in allogeneic HSCT recipients. Lancet Lond Engl 2021;398:298–9.
[103] Greenberger LM, Saltzman LA, Senefeld JW, Johnson PW, DeGennaro LJ, Nichols GL. Antibody response to SARS-CoV-2 vaccines in patients with hematologic malignancies. Cancer Cell 2021;39:1031–3.
[104] Van Oekelen O, Gleason CR, Agte S, Srivastava K, Beach KF, Aleman A, et al. Highly variable SARS-CoV-2 spike antibody responses to two doses of COVID-19 RNA vaccination in patients with multiple myeloma. Cancer Cell 2021;39:1028–30.
[105] Benda M, Mutschlechner B, Ulmer H, Grabher C, Severgnini L, Volgger A, et al. Serological SARS-CoV-2 antibody response, potential predictive markers and safety of BNT162b2 mRNA COVID-19 vaccine in haematological and oncological patients. Br J Haematol 2021. https://doi.org/10.1111/bjh.17743.
[106] Perry C, Luttwak E, Balaban R, Shefer G, Morales MM, Aharon A, et al. Efficacy of the BNT162b2 mRNA COVID-19 vaccine in patients with B-cell non-Hodgkin lymphoma. Blood Adv 2021;5:3053–61.
[107] Jurgens EM, Ketas TJ, Zhao Z, Joseph Satlin M, Small CB, Sukhu A, et al. Serologic response to mRNA COVID-19 vaccination in lymphoma patients. Am J Hematol 2021;96:E410–3. https://doi.org/10.1002/ajh.26322.
[108] Stampfer SD, Goldwater M-S, Jew S, Bujarski S, Regidor B, Daniely D, et al. Response to mRNA vaccination for COVID-19 among patients with multiple myeloma. Leukemia 2021. https://doi.org/10.1038/s41375-021-01354-7.
[109] Tadmor T, Benjamini O, Braester A, Rahav G, Rokach L. Antibody persistence 100 days following the second dose of BNT162b mRNA Covid19 vaccine in patients with chronic lymphocytic leukemia. Leukemia 2021;35:2727–30.
[110] Agbarya A, Sarel I, Ziv-Baran T, Agranat S, Schwartz O, Shai A, et al. Efficacy of the mRNA-based BNT162b2 COVID-19 vaccine in patients with solid malignancies treated with anti-neoplastic drugs. Cancers 2021;13:4191.
[111] Crombie JL, Sherman AC, Cheng C-A, Ryan CE, Zon R, Desjardins M, et al. Activity of mRNA COVID-19 vaccines in patients with lymphoid malignancies. Blood Adv 2021;5:3062–5.
[112] Ligumsky H, Safadi E, Etan T, Vaknin N, Waller M, Croll A, et al. Immunogenicity and safety of the BNT162b2 mRNA COVID-19 vaccine among actively treated cancer patients. J Natl Cancer Inst 2021. https://doi.org/10.1093/jnci/djab174.
[113] Re D, Barrière J, Chamorey E, Delforge M, Gastaud L, Petit E, et al. Low rate of seroconversion after mRNA anti-SARS-CoV-2 vaccination in patients with hematological malignancies. Leuk Lymphoma 2021:1–3. https://doi.org/10.1080/10428194.2021.1957877.
[114] Frantzen L, Cavaille G, Thibeaut S, El-Haik Y. Efficacy of the BNT162b2 mRNA covid-19 vaccine in a hemodialysis cohort. Nephrol Dial Transplant 2021;36:1756–7. https://doi.org/10.1093/ndt/gfab165.
[115] Lacson E, Argyropoulos CP, Manley HJ, Aweh G, Chin AI, Salman LH, et al. Immunogenicity of SARS-CoV-2 vaccine in dialysis. MedRxiv 2021. https://doi.org/10.1101/2021.04.08.21254779.
[116] Yanay NB, Freiman S, Shapira M, Wishahi S, Hamze M, Elhaj M, et al. Experience with SARS-CoV-2 BNT162b2 mRNA vaccine in dialysis patients. Kidney Int 2021;99:1496–8.
[117] Agur T, Ben-Dor N, Goldman S, Lichtenberg S, Herman-Edelstein M, Yahav D, et al. Antibody response to mRNA SARS-CoV-2 vaccine among dialysis patients - a prospective cohort study. Nephrol Dial Transplant 2021;36:1347–9. https://doi.org/10.1093/ndt/gfab155.
[118] Simon B, Rubey H, Treipl A, Gromann M, Hemedi B, Zehetmayer S, et al. Haemodialysis patients show a highly diminished antibody response after COVID-19 mRNA vaccination compared to healthy controls. Nephrol Dial Transplant 2021;36:1709–16.
[119] JJB Monzó, Rodríguez-Espinosa D, Soruco E, Maduell F. Weekly seroconversion rate of the mRNA-1273 SARS-CoV-2 vaccine in hemodialysis patients. Nephrol Dial Transplant 2021;36:1754–5. https://doi.org/10.1093/ndt/gfab195.
[120] Danthu C, Hantz S, Dahlem A, Duval M, Ba B, Guibbert M, et al. Humoral response after SARS-Cov-2 mRNA vaccine in a cohort of hemodialysis patients and kidney transplant recipients. J Am Soc Nephrol 2021;32:2153–8.
[121] Jahn M, Korth J, Dorsch O, Anastasiou OE, Sorge-Hädicke B, Tyczynski B, et al. Humoral response to SARS-CoV-2-vaccination with BNT162b2 (Pfizer BioNTech) in patients on hemodialysis. Vaccines 2021;9:360.

[122] Attias P, Sakhi H, Rieu P, Soorkia A, Assayag D, Bouhroum S, et al. Antibody response to the BNT162b2 vaccine in maintenance hemodialysis patients. Kidney Int 2021;99:1490–2.
[123] Chan L, Fuca N, Zeldis E, Campbell K, Shaikh A. Antibody response to mRNA-1273 SARS-CoV-2 vaccine in hemodialysis patients with and without prior COVID-19. Clin J Am Soc Nephrol 2021;16:1258–60.
[124] Grupper A, Sharon N, Finn T, Cohen R, Israel M, Agbaria A, et al. Humoral response to the Pfizer BNT162b2 vaccine in patients undergoing maintenance hemodialysis. Clin J Am Soc Nephrol 2021;16:1037–42.
[125] Zitt E, Davidovic T, Schimpf J, Abbassi-Nik A, Mutschlechner B, Ulmer H, et al. The safety and immunogenicity of the mRNA-BNT162b2 SARS-CoV-2 vaccine in hemodialysis patients. Front Immunol 2021;12:704773.
[126] Rincon-Arevalo H, Choi M, Stefanski A-L, Halleck F, Weber U, Szelinski F, et al. Impaired humoral immunity to SARS-CoV-2 BNT162b2 vaccine in kidney transplant recipients and dialysis patients. Sci Immunol 2021;6. eabj1031.
[127] Rodríguez-Espinosa D, Broseta JJ, Maduell F, Bedini JL, Vera M. Humoral response of mRNA-1273 SARS-CoV-2 vaccine in peritoneal dialysis patients. Kidney Int 2021;100:476–7.
[128] Speer C, Göth D, Benning L, Buylaert M, Schaier M, Grenz J, et al. Early humoral responses of hemodialysis patients after COVID-19 vaccination with BNT162b2. Clin J Am Soc Nephrol 2021;16:1073–8.
[129] Longlune N, Nogier MB, Miedougé M, Gabilan C, Cartou C, Seigneuric B, et al. High immunogenicity of a messenger RNA based vaccine against SARS-CoV-2 in chronic dialysis patients. Nephrol Dial Transplant 2021;36:1704–9.
[130] Kaiser RA, Haller MC, Apfalter P, Kerschner H, Cejka D. Comparison of BNT162b2 (Pfizer-BioNtech) and mRNA-1273 (Moderna) SARS-CoV-2 mRNA vaccine immunogenicity in dialysis patients. Kidney Int 2021;100:697–8.
[131] Schrezenmeier E, Bergfeld L, Hillus D, Lippert J-D, Weber U, Tober-Lau P, et al. Immunogenicity of COVID-19 tozinameran vaccination in patients on chronic dialysis. Front Immunol 2021;12:690698.
[132] Ivanauskaite G, Rimsevicius L, Avizienyte E, Vinikovas A, Maciuleviciene A, Brauklyte J, et al. Successful COVID-19 vaccination for patients on dialysis in Vilnius County. Hemodial Int 2021;25:565–6. https://doi.org/10.1111/hdi.12972.
[133] Tylicki L, Biedunkiewicz B, Dąbrowska M, Ślizień W, Tylicki P, Polewska K, et al. Humoral response to SARS-CoV-2 vaccination promises to improve the catastrophic prognosis of hemodialysis patients as a result of COVID-19. The COViNEPH Project. Pol Arch Intern Med 2021;131:797–801.
[134] Labriola L, Scohy A, Van Regemorter E, Robert A, Clerbaux G, Gillerot G, et al. Immunogenicity of BNT162b2 SARS-CoV-2 vaccine in a multicenter cohort of nursing home residents receiving maintenance hemodialysis. Am J Kidney Dis 2021:774–5. https://doi.org/10.1053/j.ajkd.2021.07.004.
[135] Elecsys® Anti-SARS-CoV-2 S. Diagnostics. n.d. https://diagnostics.roche.com/fr/fr/products/params/elecsys-anti-sars-cov-2-s.html. [Accessed 4 August 2021]. accessed
[136] Ou MT, Boyarsky BJ, Chiang TPY, Bae S, Werbel WA, Avery RK, et al. Immunogenicity and reactogenicity after SARS-CoV-2 mRNA vaccination in kidney transplant recipients taking belatacept. Transplantation 2021;105:2119–21.
[137] Marion O, Del Bello A, Abravanel F, Couat C, Faguer S, Esposito L, et al. Safety and immunogenicity of anti-SARS-CoV-2 messenger RNA vaccines in recipients of solid organ transplants. Ann Intern Med 2021;174:1336–8.
[138] Rozen-Zvi B, Yahav D, Agur T, Zingerman B, Ben-Zvi H, Atamna A, et al. Antibody response to mRNA SARS-CoV-2 vaccine among kidney transplant recipients – prospective cohort study. Clin Microbiol Infect Off Publ Eur Soc Clin Microbiol Infect Dis 2021;27:1173. e1–e4.
[139] Benotmane I, Gautier-Vargas G, Cognard N, Olagne J, Heibel F, Braun-Parvez L, et al. Low immunization rates among kidney transplant recipients who received 2 doses of the mRNA-1273 SARS-CoV-2 vaccine. Kidney Int 2021;99:1498–500.
[140] Shostak Y, Shafran N, Heching M, Rosengarten D, Shtraichman O, Shitenberg D, et al. Early humoral response among lung transplant recipients vaccinated with BNT162b2 vaccine. Lancet Respir Med 2021;9:e52–3.
[141] Midtvedt K, Tran T, Parker K, Marti H-P, Stenehjem A-E, Gøransson LG, et al. Low immunization rate in kidney transplant recipients also after dose 2 of the BNT162b2 vaccine: continue to keep your guard up. Transplantation 2021;105:e80–1.
[142] Grupper A, Rabinowich L, Schwartz D, Schwartz IF, Ben-Yehoyada M, Shashar M, et al. Reduced humoral response to mRNA SARS-CoV-2 BNT162b2 vaccine in kidney transplant recipients without prior exposure to the virus. Am J Transplant 2021;21:2719–26.
[143] Mazzola A, Todesco E, Drouin S, Hazan F, Marot S, Thabut D, et al. Poor Antibody response after two doses of SARS-CoV-2 vaccine in transplant recipients. Clin Infect Dis 2021. https://doi.org/10.1093/cid/ciab580.
[144] Rabinowich L, Grupper A, Baruch R, Ben-Yehoyada M, Halperin T, Turner D, et al. Low immunogenicity to SARS-CoV-2 vaccination among liver transplant recipients. J Hepatol 2021;75:435–8.
[145] Peled Y, Ram E, Lavee J, Sternik L, Segev A, Wieder-Finesod A, et al. BNT162b2 vaccination in heart transplant recipients: clinical experience and antibody response. J Heart Lung Transplant 2021;40:759–62.
[146] Narasimhan M, Mahimainathan L, Clark AE, Usmani A, Cao J, Araj E, et al. Serological response in lung transplant recipients after two doses of SARS-CoV-2 mRNA vaccines. Vaccines 2021;9:708.
[147] Itzhaki Ben Zadok O, Shaul AA, Ben-Avraham B, Yaari V, Ben Zvi H, Shostak Y, et al. Immunogenicity of the BNT162b2 mRNA vaccine in heart transplant recipients – a prospective cohort study. Eur J Heart Fail 2021;23:1555–9.
[148] Marinaki S, Adamopoulos S, Degiannis D, Roussos S, Pavlopoulou ID, Hatzakis A, et al. Immunogenicity of SARS-CoV-2 BNT162b2 vaccine in solid organ transplant recipients. Am J Transplant 2021;21:2913–5.
[149] Havlin J, Svorcova M, Dvorackova E, Lastovicka J, Lischke R, Kalina T, et al. Immunogenicity of BNT162b2 mRNA COVID-19 vaccine and SARS-CoV-2 infection in lung transplant recipients. J Heart Lung Transplant 2021;40:754–8.
[150] Husain SA, Tsapepas D, Paget KF, Chang J-H, Crew RJ, Dube GK, et al. Post-vaccine anti-SARS-CoV-2 spike protein antibody development in kidney transplants recipients. Kidney Int Rep 2021;6:1699–700.
[151] Korth J, Jahn M, Dorsch O, Anastasiou OE, Sorge-Hädicke B, Eisenberger U, et al. Impaired humoral response in renal transplant recipients to SARS-CoV-2 vaccination with BNT162b2 (Pfizer-BioNTech). Viruses 2021;13:756.
[152] Firket L, Descy J, Seidel L, Bonvoisin C, Bouquegneau A, Grosch S, et al. Serological response to mRNA SARS-CoV-2 BNT162b2 vaccine in kidney transplant recipients depends on prior exposure to SARS-CoV-2. Am J Transplant 2021. https://doi.org/10.1111/ajt.16726.
[153] Benotmane I, Gautier G, Perrin P, Olagne J, Cognard N, Fafi-Kremer S, et al. Antibody response after a third dose of the mRNA-1273 SARS-CoV-2 vaccine in kidney transplant recipients with minimal serologic response to 2 doses. JAMA 2021;326:1063–5.
[154] Rashidi-Alavijeh J, Frey A, Passenberg M, Korth J, Zmudzinski J, Anastasiou OE, et al. Humoral response to SARS-Cov-2 vaccination in liver transplant recipients-a single-center experience. Vaccines 2021;9:738.
[155] Guarino M, Cossiga V, Esposito I, Alessandro F, Morisco F. Effectiveness of SARS-Cov-2 vaccination in liver transplanted patients: the debate is open. J Hepatol 2021:1961–9. https://doi.org/10.1016/j.jhep.2021.07.034.
[156] Haskin O, Ashkenazi-Hoffnung L, Ziv N, Borovitz Y, Dagan A, Levi S, et al. Serological response to the BNT162b2 COVID-19 mRNA vaccine in adolescent and young adult kidney transplant recipients. Transplantation 2021. https://doi.org/10.1097/TP.0000000000003922. Ahead of print.
[157] Noble J, Langello A, Bouchut W, Lupo J, Lombardo D, Rostaing L. Immune response post-SARS-CoV-2 mRNA vaccination in kidney-transplant recipients receiving belatacept. Transplantation 2021. https://doi.org/10.1097/TP.0000000000003923. Ahead of print.
[158] Georgery H, Devresse A, Yombi J-C, Belkhir L, De Greef J, Darius T, et al. Disappointing immunization rate after 2 doses of the BNT162b2 vaccine in a Belgian cohort of kidney transplant recipients. Transplantation 2021. https://doi.org/10.1097/TP.0000000000003861. Ahead of print.
[159] Strauss AT, Hallett AM, Boyarsky BJ, Ou MT, Werbel WA, Avery RK, et al. Antibody response to SARS-CoV-2 messenger RNA vaccines in liver transplant recipients. Liver Transplant 2021. https://doi.org/10.1002/lt.26273.
[160] Hallett AM, Greenberg RS, Boyarsky BJ, Shah PD, Ou MT, Teles AT, et al. SARS-CoV-2 messenger RNA vaccine antibody response and reactogenicity in heart and lung transplant recipients. J Heart Lung Transplant 2021:2445–51. https://doi.org/10.1016/j.healun.2021.07.026. S1053–2498.
[161] Furer V, Eviatar T, Zisman D, Peleg H, Paran D, Levartovsky D, et al. Immunogenicity and safety of the BNT162b2 mRNA COVID-19 vaccine in adult patients with autoimmune inflammatory rheumatic diseases and in the general population: a multicentre study. Ann Rheum Dis 2021;80:1330–8. https://doi.org/10.1136/annrheumdis-2021-220647.
[162] Braun-Moscovici Y, Kaplan M, Braun M, Markovits D, Giryes S, Toledano K, et al. Disease activity and humoral response in patients with inflammatory rheumatic diseases after two doses of the Pfizer mRNA vaccine against SARS-CoV-2. Ann Rheum Dis 2021;80:1317–21.
[163] Deepak P, Kim W, Paley MA, Yang M, Carvidi AB, El-Qunni AA, et al. Glucocorticoids and B cell depleting agents substantially impair immunogenicity of mRNA vaccines to SARS-CoV-2. MedRxiv 2021. https://doi.org/10.1101/2021.04.05.21254656.
[164] Achiron A, Mandel M, Dreyer-Alster S, Harari G, Magalashvili D, Sonis P, et al. Humoral immune response to COVID-19 mRNA vaccine in patients with multiple sclerosis treated with high-efficacy disease-modifying therapies. Ther Adv Neurol Disord 2021;14. 17562864211012836.
[165] Spiera R, Jinich S, Jannat-Khah D. Rituximab, but not other antirheumatic therapies, is associated with impaired serological response to SARS- CoV-2 vaccination in patients with rheumatic diseases. Ann Rheum Dis 2021;80:1357–9.
[166] Simon D, Tascilar K, Fagni F, Krönke G, Kleyer A, Meder C, et al. SARS-CoV-2 vaccination responses in untreated, conventionally treated and anticytokine-treated patients with immune-mediated inflammatory diseases. Ann Rheum Dis 2021;80:1312–6.
[167] Rubbert-Roth A, Vuilleumier N, Ludewig B, Schmiedeberg K, Haller C, von Kempis J. Anti-SARS-CoV-2 mRNA vaccine in patients with rheumatoid arthritis. Lancet Rheumatol 2021;3:e470–2.
[168] Guerrieri S, Lazzarin S, Zanetta C, Nozzolillo A, Filippi M, Moiola L. Serological response to SARS-CoV-2 vaccination in multiple sclerosis patients treated with fingolimod or ocrelizumab: an initial real-life experience. J Neurol 2021. https://doi.org/10.1007/s00415-021-10663-x.
[169] Bigaut K, Kremer L, Fleury M, Lanotte L, Collongues N, de Seze J. Impact of disease-modifying treatments on humoral response after COVID-19 vaccination: a mirror of the response after SARS-CoV-2 infection. Rev Neurol (Paris) 2021:569–75. https://doi.org/10.1016/j.neurol.2021.05.001. S0035-3787.

[170] Kennedy NA, Lin S, Goodhand JR, Chanchlani N, Hamilton B, Bewshea C, et al. Infliximab is associated with attenuated immunogenicity to BNT162b2 and ChAdOx1 nCoV-19 SARS-CoV-2 vaccines in patients with IBD. Gut 2021;70:1884–93.
[171] Wong S-Y, Dixon R, Martinez Pazos V, Gnjatic S, Colombel J-F, Cadwell K, et al. Serologic response to messenger RNA coronavirus disease 2019 vaccines in inflammatory bowel disease patients receiving biologic therapies. Gastroenterology 2021;161:715–8. e4.
[172] Geisen UM, Berner DK, Tran F, Sümbül M, Vullriede L, Ciripoi M, et al. Immunogenicity and safety of anti-SARS-CoV-2 mRNA vaccines in patients with chronic inflammatory conditions and immunosuppressive therapy in a monocentric cohort. Ann Rheum Dis 2021;80:1306–11.
[173] Callejas Rubio JL, Ríos Fernández R, De la Hera Fernández J. Efficacy and safety of SARS-CoV-2 vaccine in patients with giant cell arteritis. Med Clin (Barc) 2021. https://doi.org/10.1016/j.medcli.2021.05.003.
[174] Valor-Méndez L, Tascilar K, Simon D, Distler J, Kleyer A, Schett G, et al. Correspondence on "Immunogenicity and safety of anti-SARS-CoV-2 mRNA vaccines in patients with chronic inflammatory conditions and immunosuppressive therapy in a monocentric cohort. Ann Rheum Dis 2021;80:e161. https://doi.org/10.1136/annrheumdis-2021-220898.
[175] Ammitzbøll C, Bartels LE, Bøgh Andersen J, Risbøl Vils S, Elbaek Mistegård C, Dahl Johannsen A, et al. Impaired antibody response to the BNT162b2 messenger RNA coronavirus disease 2019 vaccine in patients with systemic lupus erythematosus and rheumatoid arthritis. ACR Open Rheumatol 2021;3:622–8.
[176] Kappelman MD, Weaver KN, Boccieri M, Firestine A, Zhang X, Long MD, et al. Humoral immune response to messenger RNA COVID-19 vaccines among patients with inflammatory bowel disease. Gastroenterology 2021;161:1340–3. e2.
[177] Capuano R, Donnarumma G, Bisecco A, Grimaldi E, Conte M, d'Ambrosio A, et al. Humoral response to SARS-CoV-2 mRNA vaccine in patients with multiple sclerosis treated with natalizumab. Ther Adv Neurol Disord 2021;14. https://doi.org/10.1177/17562864211038111. 17562864211038112.
[178] Mrak D, Tobudic S, Koblischke M, Graninger M, Radner H, Sieghart D, et al. SARS-CoV-2 vaccination in rituximab-treated patients: B cells promote humoral immune responses in the presence of T-cell-mediated immunity. Ann Rheum Dis 2021. https://doi.org/10.1136/annrheumdis-2021-220781. annrheumdis-2021-220781.
[179] Ruddy JA, Boyarsky BJ, Bailey JR, Karaba AH, Garonzik-Wang JM, Segev DL, et al. Safety and antibody response to two-dose SARS-CoV-2 messenger RNA vaccination in persons with HIV. AIDS Lond Engl 2021. https://doi.org/10.1097/QAD.0000000000003017.
[180] Abo-Helo N, Muhammad E, Ghaben-Amara S, Panasoff J, Cohen S. Specific antibody response of patients with common variable immunodeficiency to BNT162b2 coronavirus disease 2019 vaccination. Ann Allergy Asthma Immunol 2021;127:501–3.
[181] Lustig Y, Sapir E, Regev-Yochay G, Cohen C, Fluss R, Olmer L, et al. BNT162b2 COVID-19 vaccine and correlates of humoral immune responses and dynamics: a prospective, single-centre, longitudinal cohort study in health-care workers. Lancet Respir Med 2021;9:999–1009.
[182] Kageyama T, Ikeda K, Tanaka S, Taniguchi T, Igari H, Onouchi Y, et al. Antibody responses to BNT162b2 mRNA COVID-19 vaccine and their predictors among healthcare workers in a tertiary referral hospital in Japan. Clin Microbiol Infect 2021. https://doi.org/10.1016/j.cmi.2021.07.042.
[183] Chodick G, Tene L, Rotem RS, Patalon T, Gazit S, Ben-Tov A, et al. The effectiveness of the TWO-DOSE BNT162b2 vaccine: analysis of real-world data. Clin Infect Dis 2021. https://doi.org/10.1093/cid/ciab438.
[184] Khan N, Mahmud N. Effectiveness of SARS-CoV-2 vaccination in a veterans affairs cohort of inflammatory bowel disease patients with diverse exposure to immunosuppressive medications. Gastroenterology 2021;161:827–36.
[185] Tenforde MW, Patel MM, Ginde AA, Douin DJ, Talbot HK, Casey JD, et al. Effectiveness of SARS-CoV-2 mRNA vaccines for preventing Covid-19 hospitalizations in the United States. MedRxiv 2021. https://doi.org/10.1101/2021.07.08.21259776.
[186] Aslam S, Adler E, Mekeel K, Little SJ. Clinical effectiveness of COVID-19 vaccination in solid organ transplant recipients. Transpl Infect Dis 2021:e13705. https://doi.org/10.1111/tid.13705.
[187] Polack FP, Thomas SJ, Kitchin N, Absalon J, Gurtman A, Lockhart S, et al. Safety and efficacy of the BNT162b2 mRNA covid-19 vaccine. N Engl J Med 2020;383:2603–15.
[188] Baden LR, El Sahly HM, Essink B, Kotloff K, Frey S, Novak R, et al. Efficacy and safety of the mRNA-1273 SARS-CoV-2 vaccine. N Engl J Med 2021;384:403–16.
[189] Voysey M, Clemens SAC, Madhi SA, Weckx LY, Folegatti PM, Aley PK, et al. 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. Lancet Lond Engl 2021;397:99–111.
[190] Sadoff J, Gray G, Vandebosch A, Cárdenas V, Shukarev G, Grinsztejn B, et al. Safety and efficacy of single-dose Ad26.COV2.S vaccine against Covid-19. N Engl J Med 2021;384:2187–201.
[191] Walsh EE, Robert W, Frenck J, Falsey AR, Kitchin N, Absalon J, et al. Safety and immunogenicity of two RNA-based covid-19 vaccine candidates. N Engl J Med 2020;383:2439–50.
[192] Sadoff J, Le Gars M, Shukarev G, Heerwegh D, Truyers C, de Groot AM, et al. Interim results of a phase 1–2a trial of Ad26.COV2.S covid-19 vaccine. N Engl J Med 2021;384:1824–35.
[193] Folegatti PM, Ewer KJ, Aley PK, Angus B, Becker S, Belij-Rammerstorfer S, et al. 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. Lancet Lond Engl 2020;396:467–78.
[194] Siegrist C-A, Ambrosioni J, Bel M, Combescure C, Hadaya K, Martin P-Y, et al. Responses of solid organ transplant recipients to the AS03-adjuvanted pandemic influenza vaccine. Antivir Ther 2012;17:893–903.
[195] Quintana LF, Serra N, De Molina-Llauradó P, Blasco M, Martinez M, Campos B, et al. Influence of renal replacement therapy on immune response after one and two doses of the A(H1N1) pdm09 vaccine. Influenza Other Respir Virus. 2013;7:809–14.
[196] Lagler H, Tobudic S, Ramharter M, Elandt K, Sperr WR, Redlberger-Fritz M, et al. Pandemic whole-virion, Vero-cell-derived, adjuvant-free influenza A H1N1 vaccine in patients with solid tumors and hematologic malignancies receiving concurrent anticancer treatment: immunogenicity, tolerability, and acceptability during the pandemic situation. Vaccine 2012;30:6864–70.
[197] Lindström V, Aittoniemi J, Salmenniemi U, Käyhty H, Huhtala H, Sinisalo M. Antibody response to the 23-valent pneumococcal polysaccharide vaccine after conjugate vaccine in patients with chronic lymphocytic leukemia. Hum Vaccine Immunother 2019;15:2910–3.
[198] Scharpé J, Peetermans WE, Vanwalleghem J, Maes B, Bammens B, Claes K, et al. Immunogenicity of a standard trivalent influenza vaccine in patients on long-term hemodialysis: an open-label trial. Am J Kidney Dis Off J Natl Kidney Found 2009;54:77–85.
[199] Broeders NE, Hombrouck A, Lemy A, Wissing KM, Racapé J, Gastaldello K, et al. Influenza A/H1N1 vaccine in patients treated by kidney transplant or dialysis: a cohort study. Clin J Am Soc Nephrol CJASN 2011;6:2573–8.
[200] Chauvat A, Benhamouda N, Gey A, Lemoine FM, Paulie S, Carrat F, et al. Clinical validation of IFNγ/IL-10 and IFNγ/IL-2 FluoroSpot assays for the detection of Tr1 T cells and influenza vaccine monitoring in humans. Hum Vaccine Immunother 2014;10:104–13.
[201] Voysey M, Clemens SAC, Madhi SA, Weckx LY, Folegatti PM, Aley PK, et al. Single-dose administration and the influence of the timing of the booster dose on immunogenicity and efficacy of ChAdOx1 nCoV-19 (AZD1222) vaccine: a pooled analysis of four randomised trials. Lancet 2021;397:881–91.
[202] Zhang K, Wu X, Shi Y, Gou X, Huang J. Immunogenicity of H5N1 influenza vaccines in elderly adults: a systematic review and meta-analysis. Hum Vaccine Immunother 2021;17:475–84.
[203] Goodwin K, Viboud C, Simonsen L. Antibody response to influenza vaccination in the elderly: a quantitative review. Vaccine 2006;24:1159–69.
[204] Jackson LA, Gurtman A, van Cleeff M, Jansen KU, Jayawardene D, Devlin C, et al. Immunogenicity and safety of a 13-valent pneumococcal conjugate vaccine compared to a 23-valent pneumococcal polysaccharide vaccine in pneumococcal vaccine-naive adults. Vaccine 2013;31:3577–84.
[205] Tohme RA, Awosika-Olumo D, Nielsen C, Khuwaja S, Scott J, Xing J, et al. Evaluation of hepatitis B vaccine immunogenicity among older adults during an outbreak response in assisted living facilities. Vaccine 2011;29:9316–20.
[206] Eisenberg RA, Jawad AF, Boyer J, Maurer K, McDonald K, Prak ETL, et al. Rituximab-treated patients have a poor response to influenza vaccination. J Clin Immunol 2013;33:388–96.
[207] Hua C, Barnetche T, Combe B, Morel J. Effect of methotrexate, anti-tumor necrosis factor α, and rituximab on the immune response to influenza and pneumococcal vaccines in patients with rheumatoid arthritis: a systematic review and meta-analysis. Arthritis Care Res 2014;66:1016–26.
[208] Yri OE, Torfoss D, Hungnes O, Tierens A, Waalen K, Nordøy T, et al. Rituximab blocks protective serologic response to influenza A (H1N1) 2009 vaccination in lymphoma patients during or within 6 months after treatment. Blood 2011;118:6769–71.
[209] Ide Y, Imamura Y, Ohfuji S, Fukushima W, Ide S, Tsutsumi C, et al. Immunogenicity of a monovalent influenza A(H1N1)pdm09 vaccine in patients with hematological malignancies. Hum Vaccine Immunother 2014;10:2387–94.
[210] Bar-Or A, Calkwood JC, Chognot C, Evershed J, Fox EJ, Herman A, et al. Effect of ocrelizumab on vaccine responses in patients with multiple sclerosis: the VELOCE study. Neurology 2020;95. e1999–2008.
[211] Subesinghe S, Bechman K, Rutherford AI, Goldblatt D, Galloway JB. A systematic review and metaanalysis of antirheumatic drugs and vaccine immunogenicity in rheumatoid arthritis. J Rheumatol 2018;45:733–44.
[212] Stapleton JT, Wagner N, Tuetken R, Bellamy AR, Hill H, Kim S, et al. High dose trivalent influenza vaccine compared to standard dose vaccine in patients with rheumatoid arthritis receiving TNF-alpha inhibitor therapy and healthy controls: results of the DMID 10-0076 randomized clinical trial. Vaccine 2020;38:3934–41.
[213] Dagan N, Barda N, Kepten E, Miron O, Perchik S, Katz MA, et al. BNT162b2 mRNA covid-19 vaccine in a nationwide mass vaccination setting. N Engl J Med 2021;384:1412–23.

[214] Haas EJ, Angulo FJ, McLaughlin JM, Anis E, Singer SR, Khan F, et al. Impact and effectiveness of mRNA BNT162b2 vaccine against SARS-CoV-2 infections and COVID-19 cases, hospitalisations, and deaths following a nationwide vaccination campaign in Israel: an observational study using national surveillance data. Lancet Lond Engl 2021;397:1819–29.
[215] Tsapepas D, Paget K, Mohan S, Cohen DJ, Husain SA. Clinically significant COVID-19 following SARS-CoV-2 vaccination in kidney transplant recipients. Am J Kidney Dis 2021;78:314–7.
[216] Malinis M, Cohen E, Azar MM. Effectiveness of SARS-CoV-2 vaccination in fully-vaccinated solid organ transplant recipients. Am J Transplant 2021;21:2916–8. https://doi.org/10.1111/ajt.16713.
[217] Ben-Tov A, Banon T, Chodick G, Kariv R, Assa A, Gazit S, et al. BNT162b2 Messenger RNA COVID-19 vaccine effectiveness in patients with inflammatory bowel disease: preliminary real-world data during mass vaccination campaign. Gastroenterology 2021:3233–9. https://doi.org/10.1053/j.gastro.2021.06.076.
[218] Lopez Bernal J, Andrews N, Gower C, Gallagher E, Simmons R, Thelwall S, et al. Effectiveness of covid-19 vaccines against the B.1.617.2 (delta) variant. N Engl J Med 2021;385:585–94.
[219] Scobie HM, Johnson AG, Suthar AB, Severson R, Alden NB, Balter S, et al. Monitoring incidence of COVID-19 cases, hospitalizations, and deaths, by vaccination status - 13 U.S. Jurisdictions, April 4-July 17, 2021. MMWR Morb Mortal Wkly Rep 2021;70:1284–90.
[220] Loubet P, Wittkop L, Tartour E, Parfait B, Barrou B, Blay J-Y, et al. A French cohort for assessing COVID-19 vaccine responses in specific populations. Nat Med 2021;27:1319–21.
[221] Schmidt T, Klemis V, Schub D, Mihm J, Hielscher F, Marx S, et al. Immunogenicity and reactogenicity of heterologous ChAdOx1 nCoV-19/mRNA vaccination. Nat Med 2021;27:1530–5.
[222] Barros-Martins J, Hammerschmidt SI, Cossmann A, Odak I, Stankov MV, Morillas Ramos G, et al. Immune responses against SARS-CoV-2 variants after heterologous and homologous ChAdOx1 nCoV-19/BNT162b2 vaccination. Nat Med 2021;27:1525–9.
[223] Lee J-H, Hong S, Im JH, Lee J-S, Baek JH, Kwon HY. Systematic review and meta-analysis of immune response of double dose of hepatitis B vaccination in HIV-infected patients. Vaccine 2020;38:3995–4000.
[224] Sodhi JS, Raja W, Zargar SA, Showkat A, Parveen S, Nisar S, et al. The efficacy of accelerated, multiple, double-dose hepatitis B vaccine against hepatitis B virus infection in cancer patients receiving chemotherapy. Indian J Gastroenterol Off J Indian Soc Gastroenterol 2015;34:372–9.
[225] Marovich M, Mascola JR, Cohen MS. Monoclonal antibodies for prevention and treatment of COVID-19. JAMA 2020;324:131–2.
[226] Olivier Epaulard, Jean-Daniel Lelièvre, Sophie Tchakamian. Stratégie de vaccination contre le Sars-Cov-2 - vaccination prioritaire de l'entourage des personnes immunodéprimées contre le SARS-CoV-2. Haute Autorité de Santé, 29 April 2021.