Seroconversion following the first, second, and third dose of SARS-CoV-2 vaccines in immunocompromised population: a systematic review and meta-analysis

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Abstract
Background: Immunocompromised (IC) patients are at higher risk of more severe COVID-19 infections than the general population. Special considerations should be dedicated to such patients. We aimed to investigate the efficacy of COVID-19 vaccines based on the vaccine type and etiology as well as the necessity of booster dose in this high-risk population.

Materials and methods: We searched PubMed, Web of Science, and Scopus databases for observational studies published between June 1st, 2020, and September 1st, 2021, which investigated the seroconversion after COVID-19 vaccine administration in adult patients with IC conditions. For investigation of sources of heterogeneity, subgroup analysis and sensitivity analysis were conducted. Statistical analysis was performed using R software.

Results: According to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses, we included 81 articles in the meta-analysis. The overall crude prevalence of seroconversion after the first (n: 7460), second (n: 13,181), and third (n: 909, all population were transplant patients with mRNA vaccine administration) dose administration was 26.17% (95% CI 19.01%, 33.99%, I^2 = 97.1%), 57.11% (95% CI: 49.22%, 64.83%, I^2 = 98.4%), and 48.65% (95% CI: 34.63%, 62.79%, I^2 = 94.4%). Despite the relatively same immunogenicity of mRNA and vector-based vaccines after the first dose, the mRNA vaccines induced higher immunity after the second dose. Regarding the etiologic factor, transplant patients were less likely to develop immunity after both first and second dose rather than patients with malignancy (17.0% vs 37.0% after first dose, P = 0.02; 38.3% vs 72.1% after second dose, P < 0.001) or autoimmune disease (17.0% vs 37.0% after first dose, P = 0.02).

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Introduction
Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was firstly reported in Wuhan, Hubei Province, China, in December 2019 [1, 2]. Due to the rapid global spread of SARS-CoV-2, leading to thousands of deaths by the coronavirus disease (COVID-19), the World Health Organization (WHO) declared a pandemic on March 12th, 2020. COVID-19 has put a massive burden on the world in the case of human lives lost, economic consequences, and increasing poverty over the last two years [3]. From the first waves of the pandemic, researchers have struggled to develop an effective and safe vaccine against this virus, and some were developed and passed the trial phase expeditiously [4].

Some vaccines have been approved by the WHO so far, including messenger RNA (mRNA) vaccines, including mRNA-1273 Moderna and BNT162b2 Pfizer BioNTech, viral vector vaccines, namely AstraZeneca and Janssen Ad26.COV2.S, and inactivated virus vaccines, including Sinovac and Sinopharm [5]. Concerning immunogenicity and safety of these vaccines, preliminary reports from phase II/III and some real-world data are available to date [6–9]; however, little attention has been paid to immunocompromised (IC) patients since such patients were not included in the primary trials of the above-mentioned vaccines [10]. IC patients, including those with primary immunodeficiencies, autoimmune diseases, malignancies, human immunodeficiency virus (HIV) infection, and those taking immunosuppressive agents, are at higher risk of more severe SARS-CoV-2 infections than the general population [11–15]. So, special considerations should be dedicated to such patients, and investigating the efficacy and safety of vaccines against SARS-CoV-2 is crucial in these patients.

Heterogeneous studies have recently assessed the immune response against SARS-CoV-2 in IC patients after receiving the first, second, or the third dose of approved vaccines, mostly by assessing the SARS-CoV-2 anti-spike or anti-receptor-binding domain (RBD) antibodies [16–18]. In this systematic review and meta-analysis, we aimed to provide a more explicit vision by systematically reviewing the literature and complementing the reported clinical outcomes around the efficacy of vaccines in IC patients.

Methods
Seroconversion frequencies following vaccination were studied using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [19] and a systematic search to locate relevant research papers.

Search strategy and databases
PubMed-MEDLINE, Scopus, and Web of Science were searched for original articles reporting the seroconversion after COVID-19 vaccine administration in adult patients with IC conditions between June 1st, 2020, and September 1st, 2021. The search terms were as follows: (((COVID-19) OR (SARS-CoV-2) OR (novel coronavirus)) AND ((vaccine) OR (vaccination) OR (vaccinated)) AND ((immunocompromised) OR (immunosuppressed) OR (corticosteroid) OR (chemotherapy) OR (cancer) OR (malignancy) OR (rheumatologic disease) OR (immunodeficiency) OR (autoimmune) OR (AIDS) OR (HIV) OR (transplant))).

Selection criteria
Studies examining the prevalence of seroconversion following COVID-19 immunization in IC patients met the inclusion criteria. The papers considered in this review satisfied the following criteria: (1) Population: studies including ≥ 30 IC patients. IC patients included those receiving chemotherapy for solid organ or hematologic malignancies, human immunodeficiency virus infections than the general population [11–15]. So, special considerations should be dedicated to such patients, and investigating the efficacy and safety of vaccines against SARS-CoV-2 is crucial in these patients.

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Conclusion: The rising pattern of seroconversion after boosting tends to be promising. In this case, more attention should be devoted to transplant patients who possess the lowest response rate.

Keywords: COVID-19, SARS-CoV-2, Vaccination, Immunocompromised patient, Malignancy, Transplantation, Autoimmune, Efficacy
literature; and (5) non-human experiments. Two reviewers separately conducted a consensual evaluation of the literature.

**Data extraction**
Two experts independently assessed eligible studies and retrieved the following data from each included publication: author, publication date, country of origin, study design, study sample size, the definition of IC conditions, inclusion and exclusion criteria, number of IC patients, variables matched, male/female ratio, mean age, duration of disease, type and etiology of immunodeficiency and its proportion in the total population, and the type of vaccine. Any discrepancies in data extraction were handled by discussion or consultation with a third expert.

**Quality assessment**
We evaluated the included studies using the National Institutes of Health (NIH) quality assessment tool [20]. If an element of the criteria was inadequately addressed, not applicable, or not reported in a study, and it could not be identified indirectly, we did not allocate a score to that element. For cohort and cross-sectional studies, 11–14 was considered good, 6–10 fair, and 0–5 poor. The corresponding values were 7–9, 4–6, and 0–3 for the case series and 9–12, 5–8, and 0–4 for case-control studies, respectively.

**Statistical analysis**
We used the ‘metaprop’ function to estimate Der Simonian and Laird’s pooled effect on the prevalence of seroconversion following vaccine delivery using a random-effect model. A forest plot was created to depict the summary of meta-analysis findings and heterogeneity. A funnel plot was used to check for publication bias, and Egger’s regression tests were used to test for it more objectively, with a p < 0.05 deemed to suggest possible publication bias. The Cochrane Q statistic was used to assess between-study heterogeneity [21]. I² was used to assess between-study heterogeneity, with values of 0, 25, 50, and 75% representing no, low, medium, and substantial heterogeneity, respectively [22]. A leave-one-out sensitivity analysis was used to determine the impact of a single study on the total meta-analysis estimate (Additional file 1: Figs. S1-3). The final results were given as text, tables, and figures. All computations and visualizations were carried out using R version 4.0.4 (R Core Team [2020]. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria), and STATA 16 (StataCorp. 2019. Stata Statistical Software: Release 16. College Station, TX: StataCorp LLC) for Egger’s plots. We used following packages: “meta” (version 4.17-0), “metafor” (version 2.4-0), “dmetar” (version 0.0-9), and “tidyverse” (version 1.3.0). All forest plots, funnel plots, and the drapery plot were designed using R. A p < 0.05 was considered statistically significant.

**Results**

**Selection of studies**
After implementing our strategy, we reached a total of 2093 research publications. Then, we screened both the titles and abstracts for relevant studies and 151 research articles were selected for full-text screening. Ultimately, 80 research publications [23–102] were included in our systematic review and meta-analyses (Fig. 1; PRISMA diagram).

**Study characteristics**
Table 1 summarizes the characteristics of the 80 included studies, which were published in 2021. Forty [23–62] studies assessed seroconversion in immunocompromised patients after the administration of the first dose of the vaccines. Also, 64 [23–25, 28, 30, 33–40, 42, 43, 45–50, 52, 60–101] studies were included as they evaluated seroconversion after the second injection in immunocompromised patients. Lastly, seven [28, 38, 61, 87, 97, 100, 102] studies investigated seroconversion and its prevalence after the third dose of the vaccines. Considering the type of the administered vaccine, we grouped the included studies as mRNA, vector, and inactivated virus. Moreover, regarding the etiology, studies were grouped into autoimmune, malignancy, and transplant.

Quality assessment of the included studies is presented in Additional file 1: Table S1. The majority of the studies (n = 64) were of good quality and 16 had fair quality.

**Meta-analysis**

**First dose**
Results of overall efficacy and between-group meta-analyses following the first, second, and third doses are presented in Table 2. The crude overall prevalence of seroconversion after the first dose administration in the pooled sample of 7460 individuals was 26.17% (95% CI: 19.01%; 33.99%, test of heterogeneity: I² = 97.1%, p < 0.0001). Considering the type of vaccine, the test for subgroup differences showed significant results (p = 0.04, Fig. 2A). To investigate more, we conducted a pair-wised analysis to find whether there is a significant difference between mRNA and vector group. Accordingly, no significant difference was observed (p = 0.17). In addition, a pair-wised meta-analysis of combined group of mRNA and vector vaccines compared to inactivated group demonstrated a significant difference (30% vs. 18%, respectively; p = 0.04). Regarding the etiology, our primary analysis demonstrated a significant
between-group difference ($p = 0.02$, Fig. 2B). Moreover, pair-wised analysis showed that the difference between malignancy and autoimmune group was not statistically significant ($p = 0.95$); however, malignancy vs. transplant (37% vs. 17%, $p = 0.01$) and autoimmune vs. transplant (36% vs. 17%, $p = 0.04$) exhibited statistically significant differences. Eggers’ test does not indicate the presence of funnel plot asymmetry ($p = 0.68$); thus, the funnel plot implied no publication bias (Fig. 3A). There were no significant changes in the pooled prevalence or heterogeneity after eliminating each study in the sensitivity analysis (leave-one-out analysis) (Additional file 1: Fig. S1). As a result, none of the studies were able to explain the observed heterogeneity of results.

**Second dose**

Overall seroconversion prevalence following the second dosage in the pooled sample of 13,181 patients was 57.11% (95% CI: 49.22%; 64.83%, test of heterogeneity: $I^2 = 98.4\%$, $p < 0.01$). Given the vaccine’s type, the test for subgroup differences yielded significant findings ($p < 0.01$, Fig. 4A). We performed a pair-wised analysis to see if the mRNA and vector groups differed significantly. As a result, a large disparity was discovered ($p < 0.0001$), mainly due to various patient
Table 1 Details of the data presented by the included studies

| Study (first author) | Country                  | Study design        | Total sample size | Case group | Male% | Age (mean ± SD) (median [IQR]*) | Etiology of IC condition | Type of vaccine |
|----------------------|--------------------------|---------------------|-------------------|------------|-------|--------------------------------|--------------------------|-----------------|
| Addeo, A.            | Switzerland and USA      | Prospective cohort  | 131               | 131        | 55    | 63 [55–69]*                   | Malignancy               | n = 30 (BNT162b2 (Pfizer/BionTech)) or n = 93 (mRNA-1273 (Moderna)) |
| Agbarya, A.          | Israel                   | Cross-sectional     | 355               | 140        | 54    | 65.3 ± 1.4                   | Malignancy               | BNT162b2 (Pfizer/BionTech) |
| Agha, M.             | USA                      | Prospective cohort  | 67                | 67         | 52.2  | 71 [65–77]*                  | Malignancy               | BNT162b2 (Pfizer/BionTech) |
| Ammitzbøll, C.       | Denmark                  | Retrospective cohort| 134               | 134        | 67.1  | NA                            | Autoimmune               | BNT162b2 (Pfizer/BionTech) |
| Benotmane, I.        | France                   | Cross-sectional     | 241               | 241        | 64.7  | 57.7 [49.3-67.6]*            | Transplant               | mRNA-1273 (Moderna) |
| Benotmane, I.        | France                   | Prospective cohort  | 159               | 159        | 61.6  | 57.6 [49.6-66.1]*            | Transplant               | mRNA-1273 (Moderna) |
| Bertrand, D.         | France                   | Retrospective cohort| 55                | 45         | 51    | 63.5±16.3                    | Autoimmune               | BNT162b2 (Pfizer/BionTech) |
| Boeckel, L.          | Netherlands              | Prospective cohort  | 921               | 632        | 33    | 63±11                         | Autoimmune               | ChAdOx1 nCoV-19 (AstraZeneca), BNT162b2 (Pfizer/BionTech), CX-024414 (elasomeran; Moderna), and Ad.26.COV2.S (Janssen) |
| Boyarsky, B.         | USA                      | Prospective cohort  | 1040              | 1012       | NA    | 60.0 [45.7-68.1]*            | Transplant               | BNT162b2 (Pfizer/BionTech) |
| Boyarsky, B.         | USA                      | Prospective cohort  | 436               | 423        | 39    | 55.9 [41.3-67.4]*            | Transplant               | n = 223 (BNT162b2 (Pfizer/BionTech)) or n = 204 (mRNA-1273 (Moderna)) |
| Boyarsky, B.         | USA                      | Prospective cohort  | 123               | 123        | 5     | 50 [41–61]*                  | Autoimmune               | n = 64 (BNT162b2 (Pfizer/BionTech)) or n = 59 (mRNA-1273 (Moderna)) |
| Boyarsky, B.         | USA                      | Prospective cohort  | 658               | 658        | 50    | NA                            | Transplant               | n =100 (BNT162b2 (Pfizer/BionTech)) or n =99 (mRNA-1273 (Moderna)) |
| Boyarsky, B.         | USA                      | Prospective cohort  | 737               | 737        | 42    | 56 [42–60]*                  | Transplant               | n = 12 (Ad26 (JANSSEN/JOHNSON&JOHNSON)) or n = 725 (mRNA vaccine) |
| Braun-Moscovici, Y.  | Israel                   | Prospective cohort  | 290               | 264        | 24    | 57.6 ± 13.18                 | Autoimmune               | BNT162b2 (Pfizer/BionTech) |
| Cao, J.              | USA                      | Retrospective cohort| 47                | 37         | 72.9  | 64 [50–69]*                  | Transplant               | BNT162b2 (Pfizer/BionTech) or mRNA-1273 (Moderna) |
| Chavarot, N.         | France                   | Retrospective cohort| 97                | 97         | 58    | 63.5 [51–72]*                | Transplant               | BNT162b2 (Pfizer/BionTech) |
| Chavarot, N.         | France                   | Retrospective cohort| 101               | 101        | 67.3  | 64 [53–73]*                  | Transplant               | BNT162b2 (Pfizer/BionTech) |
| Chevallier, P.       | France                   | Prospective cohort  | 138               | 112        | 59.8  | 57 [20–75]*                  | Transplant               | BNT162b2 (Pfizer/BionTech) |
| Study (first author) | Country     | Study design  | Total sample size | Case group No. of cases | Male% | Age (mean ± SD) (median [IQR]*) | Etiology of IC condition | Type of vaccine |
|---------------------|-------------|---------------|-------------------|-------------------------|-------|-------------------------------|--------------------------|-----------------|
| Chiang, T. P.       | USA         | Prospective cohort | 1039             | 1039                    | 6.1   | NA                            | Autoimmune               | n = 45 (Ad26 (JANSSEN/JOHNSON & JOHNSON)) or n = 994 (mRNA vaccine) |
| Cohen, D.           | Israel      | Prospective cohort | 137              | 137                     | 54.7  | 68.5                          | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Cucchiari, D.       | Spain       | Prospective cohort | 148              | 117                     | 67.3  | 59.0 ± 52.4                   | Transplant               | mRNA-1273 (Moderna) |
| Danthu, C.          | France      | Prospective cohort | 159              | 74                      | 61.1  | 64.8 ± 11.5                   | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Del Bello, A.       | France      | Retrospective cohort | 396              | 396                     | 65    | 59 ± 15                       | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Easdale, S.         | UK          | Retrospective cohort | 55               | 55                      | 61.8  | 50 [18–73]*                   | Transplant               | n = 21 (BNT162b2 (Pfizer/BionTech)) or n = 34 (AstraZeneca ChAdOx1 nCoV-19 vaccine (AZ)) |
| Ehmsen, S.          | Denmark     | Prospective cohort | 524              | 524                     | NA    | NA                            | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) or mRNA-1273 (Moderna) |
| Eliakim-Raz, N.     | Israel      | Prospective cohort | 161              | 95                      | 58    | 65 [56–72]*                   | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Firket, L.          | USA         | Retrospective cohort | 40               | 20                      | 45    | 51.2                          | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Furer, V.           | Israel      | Prospective cohort | 807              | 686                     | 30.7  | 59 [19–88]*                   | Autoimmune               | BNT162b2 (Pfizer/Bion-Tech) |
| Gavriatopoulou, M.  | Greece      | Prospective cohort | 271              | 58                      | 48.2  | 75 [63–81]*                   | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) or AZD1222 vaccine (ASTRAZENECA/OXFORD) |
| Geisen, UM.         | Germany     | Retrospective cohort | 68               | 42                      | 35.7  | 50.5                          | Autoimmune               | BNT162b2 (Pfizer/Bion-Tech) or mRNA-1273 (Moderna) |
| Ghandili, S.        | Germany     | Retrospective cohort | 82               | 82                      | 59.8  | 67.5 [40–85]*                 | Malignancy               | mRNA or AZD1222 (ASTRAZENECA/OXFORD) |
| Goshen-Lago, T.     | Israel      | Prospective cohort | 493              | 232                     | 57    | 66                            | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Grupper, A.         | Israel      | Retrospective cohort | 151              | 136                     | 81.7  | 58.6                          | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Hagin, D.           | Israel      | Prospective cohort | 26               | 26                      | 42.4  | 48.4                          | Hereditary or Acquired immunodeficiency | BNT162b2 (Pfizer/Bion-Tech) |
| Hall, V. G.         | Canada      | Prospective cohort | 127              | 127                     | 69.3  | 66.2 [63.4–70.6]*             | Transplant               | mRNA-1273 (Moderna) |
| Harrington, P.      | UK          | Retrospective cohort | 21               | 21                      | 33.3  | 52.4                          | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Haskin, O.          | Israel      | Prospective cohort | 52               | 38                      | 66    | 18.6 ± 2.8                    | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Havlin, J.          | Czech Republic | Prospective cohort | 48               | 48                      | 60.4  | 52.1 ± 14.3                   | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Herishanu, Y.       | Israel      | Prospective cohort | 219              | 167                     | 67.1  | 71 [63–76]*                   | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Study (first author) | Country | Study design | Total sample size | Case group No. of cases | Male% | Age (mean ± SD) (median [IQR]*) | Etiology of IC condition | Type of vaccine |
|---------------------|---------|--------------|-------------------|------------------------|-------|------------------------------|--------------------------|--------------------------|
| Herrera, S.         | Spain   | Prospective cohort | 104              | 104                    | 79.8  | 60*                          | Transplant               | mRNA-1273 (Moderna)   |
| Herzog Tzarfati, K. | Israel  | Prospective cohort | 423              | 315                    | 0.56  | 71 [61–78]*                  | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Hod, T.             | Israel  | Prospective cohort | 322              | 120                    | 80    | 59.7 ± 13                    | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Holden, I.K.        | Denmark | Prospective cohort | 80               | 79                     | 55    | 58.9 [47.9-66.8]*            | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Iacono, D.          | Italy   | Cross-sectional | 108              | 36                     | 41.6  | 82*                          | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Itzhaki Ben Zadok, O.| Israel | Prospective cohort | 39               | 39                     | 83    | 61 [44–69]*                  | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Karacin, C.         | Turkey  | Prospective cohort | 47               | 47                     | 61.7  | 73 [64–80]*                  | Malignancy               | CoronaVac               |
| Kennedy, NA.        | UK      | Prospective cohort | 1293             | 1293                   | NA    | NA                           | Autoimmune               | n = 589 (BNT162b2 (Pfizer/BionTech)) or n = 704 (ChAdOx1 or AZD1222 (ASTRAZENECA/OXFORD)) |
| Korth, J.           | Germany | Prospective cohort | 46               | 23                     | 48    | 57.7                         | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Malard, F.          | France  | Retrospective cohort | 225             | 195                    | 60    | 68.9*                        | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Marinaki, S.        | Greece  | Prospective cohort | 150              | 34                     | 79.4  | 60 [49.1-68.4]*             | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Massarweh, A.       | Israel  | Prospective cohort | 180              | 102                    | 57    | 66 [56–72]*                  | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Mazzola, A.         | France  | Retrospective cohort | 168             | 143                    | 71.3  | 61 [55–67]*                  | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Medeiros-Ribeiro, A. C., | Brazil | Prospective cohort | 1092            | 910                    | 23.1  | 51 [40–60]*                  | Autoimmune               | CoronaVac               |
| Monin, L.           | UK      | Prospective cohort | 205              | 151                    | 52    | 73 [64.5–79.5]*             | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Narasimhan, M.      | USA     | Retrospective cohort | 73               | 73                     | 74    | 65 [53.5-69.5]*             | Transplant               | n = 48 (BNT162b2 (Pfizer/BionTech)) or n = mRNA-1273 (Moderna) |
| Noble, J.           | France  | Prospective cohort | 57               | 57                     | 68.5  | 62 ± 13                      | Transplant               | mRNA-1273 (Moderna)   |
| Ou, M. T.           | USA     | Prospective cohort | 609              | 585                    | 40    | 58 [45–68]*                  | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Palich, R.          | France  | Retrospective cohort | 135             | 110                    | 40    | 66 [54–74]*                  | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Peled, Y.           | Israel  | Prospective cohort | 77               | 77                     | 64    | 62 [49–68]*                  | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Pimpinelli, F.      | Italy   | Prospective cohort | 128              | 92                     | 53.2  | 70 [28–80]*                  | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Prendecchi, M.      | UK      | Prospective cohort | 119              | 119                    | 52.1  | 52 [39.9-63.9]*             | Autoimmune               | n = 85 (BNT162b2 (Pfizer/BionTech)) or n = 34 (ChAdOx1 or AZD1222 (ASTRAZENECA/OXFORD)) |
| Rabinowich, L.      | Israel  | Cross-sectional | 105              | 80                     | 70    | 60.1                         | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
Table 1 (continued)

| Study (first author) | Country  | Study design | Total sample size | Case group No. of cases | Male% | Age (mean ± SD) (median [IQR]*) | Etiology of IC condition | Type of vaccine |
|----------------------|----------|--------------|-------------------|-------------------------|-------|-------------------------------|--------------------------|-----------------|
| Rashidi-Alavijeh, J.  | Germany  | Prospective cohort | 63               | 43                      | 60.5  | 57 [49–64]*                  | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Reuken, P.           | Germany  | Prospective cohort | 55               | 28                      | 53.6  | 42 [36–59]*                 | Hereditary or Acquired immunodeficiency | BNT162b2 (Pfizer/Bion-Tech) |
| Rincon-Arevalo, H.   | Germany  | Prospective cohort | 75               | 40                      | 70    | 62.4 [51.25–69.5]*           | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Rozen-Zvi, B.        | Israel   | Prospective cohort | 308              | 308                     | 64    | 57.5 ± 13.8                 | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Ruddy, J. A.         | USA      | Prospective cohort | 404              | 404                     | 4     | 44 [36–57]*                 | Autoimmune               | BNT162b2 (Pfizer/Bion-Tech) |
| Sattler, A.          | Germany  | Prospective cohort | 78               | 39                      | 71.8  | 57.3                         | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Schramm, R.          | Germany  | Prospective cohort | 100              | 50                      | 64    | 55 ± 10                      | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Seyahi, E.           | Turkey   | Cross-sectional | 382              | 82                      | 35.4  | 42.2 ± 10                   | Autoimmune               | BBIBP-Cov (Sinopharm) |
| Strauss, A.          | USA      | Prospective cohort | 161              | 161                     | 43    | 64 [48–69]*                 | Transplant               | BNT162b2 (Pfizer/Bion-Tech) or mRNA-1273 (Moderna) |
| Stumpf, J.           | Germany  | Prospective cohort | 3100             | 368                     | 65.5  | 57.3 ± 13.7                 | Transplant               | n = 103 (BNT162b2 (Pfizer/BionTech)) or n = 265 (mRNA-1273 (Moderna)) |
| Stumpf, J.           | Germany  | Prospective cohort | 71               | 48                      | 63    | 57±14.4                     | Transplant               | BNT162b2 (Pfizer/Bion-Tech) |
| Terpos, E.           | Greece   | Prospective cohort | 152              | 48                      | 60.4  | 83*                          | Malignancy               | BNT162b2 (Pfizer/Bion-Tech) |
| Terpos, E.           | Greece   | Prospective cohort | 59               | 59                      | 61    | 66 [61–76]*                 | Malignancy               | BNT162b2 or AZD1222 |
| Terpos, E.           | Greece   | Prospective cohort | 502              | 276                     | 54.7  | 74 [62–80]*                 | Malignancy               | BNT162b2 or AZD1222 |
| Thakkar, A.          | USA      | Retrospective cohort | 200              | 200                     | 42    | 67 [27–90]*                 | Malignancy               | n = 180 (mRNA vaccines) or n = 20 (AD26. COV2.S) |
| Werbel, WA.          | USA      | Retrospective cohort | 30               | 30                      | 43.3  | 57 [44–62]*                 | Transplant               | n = 17 (BNT162b2 (Pfizer/BionTech)) or n = 13 (mRNA-1273 (Moderna)) |
| Yanay, NB.           | Israel   | Retrospective cohort | 204              | 204                     | 63.8  | 57.7 [49.4–67.5]*           | Transplant               | BNT162b2 (Pfizer/Bion-Tech) or mRNA-1273 (Moderna) |
| Yi, SG.              | USA      | Prospective cohort | 176              | 145                     | NA    | NA                          | Transplant               | BNT162b2 (Pfizer/Bion-Tech) or mRNA-1273 (Moderna) |

*reported values are median [interquartile range (IQR)]; otherwise are mean ± standard deviation (SD)

recruitment methods. Furthermore, a significant difference was found in a pair-wised meta-analysis comparing the combined group of mRNA and vector vaccines to the inactivated group (83% vs. 76%, respectively; $p = 0.04$). A substantial between-groups difference was found with regards to the etiology ($p < 0.01$, Fig 4B). In addition, a pair-wise comparison of malignancy vs. transplant (72% vs. 38%, $p < 0.001$) and autoimmune vs. transplant (80% vs. 38%, $p < 0.0001$) groups found statistically significant differences between the analyzed groups; however, malignancy vs. autoimmune did not show any significant difference (72% vs. 80%, $p = 0.34$). Using Eggers’ test, there was no evidence of asymmetry in the funnel plot ($p = 0.06$),
### Table 2: Results of between-group meta-analyses

| Vaccination dose | Sub-group                        | Comparison                  | No. studies | No. observations | No. events | Meta-analysis | 95% Confidence interval (%) | P value | Heterogeneity | P value |
|------------------|----------------------------------|-----------------------------|-------------|-----------------|------------|---------------|-----------------------------|---------|--------------|---------|
|                  |                                  |                             |             |                 |            | Effect size (%) |                           |         |              |         |
|                  |                                  |                             |             |                 |            | 95% Confidence interval (%) |                           |         |              |         |
|                  |                                  |                             |             |                 |            | P value       | I² (%)                     |         |              |         |
| First dose       | Overall                          |                             | 45          | 7460            | 1979       | 26.17         | 19.01, 33.99               | –       | 97.1         | < 0.0001 |
|                  | Type of vaccine                  | mRNA                        | 35          | 4894            | 1147       | 24.02         | 15.87, 33.32               | 0.0392  | 97.1         | –        |
|                  |                                  | mRNA or vector              | 4           | 1107            | 469        | 30.88         | 18.27, 44.53               | 92.9    |              |          |
|                  |                                  | Vector                      | 5           | 549             | 193        | 44.59         | 16.8, 74.26                | 90.8    |              |          |
|                  |                                  | Inactivated                  | 1           | 910             | 170        | 18.68         | 16.21, 21.28               | –       |              |          |
|                  | Type of vaccine pair-wised       | mRNA versus vector          | 39          | 5443            | 1340       | 25.89         | 17.82, 34.85               | 0.1790  | 97           | < 0.0001 |
|                  | Etiology                         | Malignancy                  | 13          | 1465            | 498        | 37.05         | 23.19, 52.05               | 0.0226  | 96.4         | –        |
|                  |                                  | Transplant                  | 23          | 3265            | 507        | 17.01         | 9.44, 26.15                | 94.8    |              |          |
|                  |                                  | Autoimmune                  | 9           | 2730            | 974        | 36.4          | 20.35, 54.15               | 97.7    |              |          |
|                  | Etiology pair-wised              | Malignancy versus autoimmune| 22          | 4195            | 1472       | 36.76         | 26.3, 47.88                | 0.9514  | 96.9         | < 0.0001 |
|                  |                                  | Malignancy versus transplant | 36          | 4730            | 1005       | 23.73         | 16.07, 32.32               | 0.0171  | 96.3         | < 0.0001 |
|                  |                                  | Autoimmune versus transplant | 32          | 5995            | 1481       | 22.07         | 14.34, 30.88               | 0.0404  | 97.3         | < 0.0001 |
| Second dose      | Overall                          |                             | 70          | 13181           | 8326       | 57.11         | 49.22, 64.83               | –       | 98.4         | < 0.0001 |
|                  | Type of vaccine                  | mRNA                        | 63          | 10441           | 6651       | 56.41         | 48.01, 64.64               | < 0.0001| 98.1         | –        |
|                  |                                  | mRNA or vector              | 2           | 908             | 777        | 36.28         | 23.19, 52.05               | 98.3    |              |          |
|                  |                                  | Vector                      | 2           | 771             | 134        | 19.12         | 11.27, 28.37               | 49.7    |              |          |
|                  |                                  | Inactivated                  | 3           | 1061            | 764        | 7.58          | 5.81, 9.46                 | 91.3    |              |          |
|                  | Type of vaccine pair-wised       | mRNA versus vector          | 65          | 11212           | 6785       | 55.28         | 46.98, 63.44               | < 0.0001| 98.4         | < 0.0001 |
|                  | Etiology                         | Malignancy                  | 18          | 2879            | 2076       | 72.15         | 59.24, 83.45               | < 0.0001| 97.6         | –        |
|                  |                                  | Transplant                  | 36          | 5836            | 2493       | 38.29         | 29.93, 46.99               | 96.2    |              |          |
|                  |                                  | Autoimmune                  | 15          | 4440            | 3737       | 80.25         | 68.08, 90.14               | 96.7    |              |          |
|                  | Etiology pair-wised              | Malignancy versus autoimmune| 33          | 7319            | 5815       | 75.9          | 67.07, 83.76               | 0.3471  | 97.5         | < 0.0001 |
|                  |                                  | Malignancy versus transplant | 54          | 8715            | 4571       | 49.93         | 41.36, 58.51               | < 0.0001| 97.8         | < 0.0001 |
|                  |                                  | Autoimmune versus transplant | 51          | 10276           | 6230       | 51.21         | 41.94, 60.44               | < 0.0001| 98.6         | < 0.0001 |
| Third dose       | Overall                          |                             | 7           | 909             | 505        | 48.65         | 36.43, 62.79               | –       | 94.4         | < 0.0001 |

* mRNA, messenger ribonucleic acid*
suggesting no publication bias (Fig. 3B). After excluding each study in the sensitivity analysis (leave-one-out analysis), the aggregated prevalence and heterogeneity did not change (Additional file 1: Fig S2). For this reason, no one study could account for this wide range of outcomes.

Notably, considering immunocompromised patients due to autoimmune diseases on anti-TNF treatment, the seroconversion prevalence was estimated as 86.07% (95% CI: 63.16%; 99.23%, test of heterogeneity: I² = 99.1%, p < 0.01).
Fig. 3  Counter-enhanced funnel plots regarding the publication bias following the first dose (A), second dose (B), and third dose (C) of vaccination.
Fig. 4 Forest plot of seroconversion proportions (prevalence) regarding the type of vaccine (A) and etiology of immunodeficiency (B) following the second dose of vaccine.

A

B
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Third dose
All the included original studies in this analysis measured seroconversion after three doses of mRNA vaccines in transplant recipients. Overall prevalence of seroconversion in the combined sample of 909 transplant patients following the third dose of vaccine was 48.65% (95% CI: 34.63%; 62.79%, test of heterogeneity: $I^2 = 94.4\%$, $p < 0.0001$, Fig 5). Eggers' test revealed no indication of funnel plot asymmetry ($p = 0.18$), confirming that there was no publication bias (Fig. 3C). The pooled prevalence and heterogeneity remained unchanged after the sensitivity analysis (leave-one-out analysis) when each study was excluded (Additional file 1: Fig. S3). Thus, no single study could explain the heterogeneity of outcomes.

Discussion
The pooled findings demonstrated a growing pattern of seroconversion rate after the administration of the second dose of COVID-19 vaccine compared to the first dose regardless of either vaccine type or the etiology of immunosuppression. Our findings also revealed a better response to mRNA vaccines compared to vector vaccines reaching significance after the administration of the second dose. In addition, transplant patients responded less robust compared to other IC patients regardless of the number of doses. It is worth mentioning that all the studies included in the pooled analysis of third-dose booster evaluated transplant patients; nevertheless, the rising pattern of seroconversion was observed even in this group of patients compared to the findings from both the first and second doses.

Viral vectors are modified viruses utilized to deliver the immunogenic part of the target virus [103]. On the other hand, mRNA vaccines deploy mRNAs coding specific viral proteins to trigger an immune response [103]. mRNA and vector vaccines seem to induce immunity with different mechanisms in healthy controls. Induction of SARS-CoV-2–specific IgG and neutralizing antibodies seems to be more pronounced with mRNA priming, while cellular immunity (including both SARS-CoV-2–specific CD4 and CD8 T cell levels) tends to be induced more robustly after vector priming [104]. However, this difference has been less prominent in IC patients [104]. Although our findings revealed higher rates of seroconversion after the second dose of mRNA vaccines, antibody assessment might be insufficient to compare immune response, and cellular immunity should be assessed as well [104].

Data regarding inactivated vaccines are rare; however, our findings show a significant difference between inactivated vaccines and combined groups of mRNA and vector vaccines. A previous report has also implicated lower efficacy of inactivated vaccines compared to vector vaccines in terms of antibody level and neutralization in immunosuppressed patients with rheumatic diseases [105]. These findings should be interpreted with caution as more studies are needed to unravel the efficacy of inactivated vaccines.

Intriguingly, a lower seroconversion rate was observed in transplant patients compared to other IC patients, even though a rising response rate was observed after boosting in this group of patients. Generally, transplant patients receive drugs that interfere with T and B cell activation and proliferation, posing an obstacle in the way of antibody generation [106]. Conspicuously, boosting seems to raise an immune response in all IC patients according to our findings, the fact which was observed with previous vaccines such as influenza [107].

Although we showed an acceptable rate of seroconversion among patients using anti-TNF therapy, reports show a persistent reduction in the titers of
anti-SARS-CoV-2 spike protein antibody with time in patients with inflammatory bowel disease (IBD) who are on anti-TNF treatments [108]. While anti-TNF therapies can mitigate detrimental outcomes in severe COVID-19 due to dampening of the systemic inflammatory response, the reduction of antibodies over time might necessitate considering booster doses in these patients [108, 109].

We should mention that our study has some limitations. There was a lack of data regarding HIV and other hereditary or acquired immunodeficiency disorders and also inactivated vaccines. Besides, we included studies with both prospective and retrospective designs, which may decrease the level of evidence.

**Conclusion**

For the first time, this meta-analysis compared seroconversion rate after administering different types of COVID-19 vaccines in IC patients at different time points of vaccination. The rising pattern of seroconversion after boosting tends to be promising; however, more attention should be devoted to transplant patients who possess the lowest response rate.

**Supplementary Information**

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**Competing interests**

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

**Additional file 1. Figure S1** Results of Sensitivity analysis (leave-one-out analysis) of the First Dose meta-analysis (I² and effect size plot). **Figure S2** Results of Sensitivity analysis (leave-one-out analysis) of the Second Dose meta-analysis (I² and effect size plot). **Figure S3** Results of Sensitivity analysis (leave-one-out analysis) of the Third Dose meta-analysis (I² and effect size plot). **Table S1** Quality assessment using NIH tool.

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**References**

1. Wu F, Zhao S, Yu B, Chen Y-M, Wang W, Song Z-G, et al. A new coronavirus associated with human respiratory disease in China. Nature. 2020;579(7798):265–9.
2. Zhou P, Yang X-L, Wang X-G, Hu B, Zhang L, Zhang W, et al. A pneumonia outbreak associated with a new coronavirus of probable bat origin. Nature. 2020;579(7798):270–3.
3. Ciotti M, Ciccozzi M, Terni noni A, Jiang W-C, Wang C-B, Bernardini S. The COVID-19 pandemic. Critical Rev Clin Lab Sci. 2020;57(6):365–88.
4. Mehran E, Dadras O, Afsahi AM, Karimi A, MohsseniPour M, Mirzapour P, et al. Vaccines for COVID-19: a systematic review of feasibility and effectiveness. Infect Disord Drug Targets. 2022;22(2):e230921196758.
5. Shekhar R, Garg I, Pal S, Kotewar S, Sheikh AB. COVID-19 vaccine booster: to boost or not to boost. Infect Dis Rep. 2021;13(4):924–9.
6. Baden LR, El Sahly HM, Essink B, Kottoff K, Frey S, Novak R, et al. Efficacy and safety of the mRNA-1273 SARS-CoV-2 vaccine. N Engl J Med. 2021;384(5):403–16.
7. 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.
8. Knoll MD, Wonodi C. Oxford-AstraZeneca COVID-19 vaccine efficacy. The Lancet. 2021;397(10269):72–4.
9. Thomas SJ, Moreira ED Jr, Kitchin N, Absalon J, Gurtman A, Lockhart S, et al. Safety and efficacy of the BNT162b2 mRNA Covid-19 vaccine through 6 months. N Engl J Med. 2021;385(19):1761–73.
10. Sonani B, Aslam F, Goyal A, Patel J, Bansal P. COVID-19 vaccination in immunocompromised patients. Clin Rheumatol. 2021;40(2):e2037069-e.
11. Fung M, Babik JM. COVID-19 in immunocompromised hosts: what we know so far. Clin Infect Dis. 2021;72(2):340–50.
12. Tesoriero JM, Swain C-AE, Pierce JI, Zamboni L, Wu M, Holtgrave DR, et al. COVID-19 outcomes among persons living with or without diagnosed HIV infection in New York State. JAMA Netw Open. 2021;4(2):e2037069-e.
13. Haidar G, Mellors JW. Improving the outcomes of immunocompromised patients with COVID-19. Clin Infect Dis. 2021;73:e1397.
14. Salahshour F, Mehrabinejad M-M, Toosi MN, Gitty M, Ghaanaei H, Shakiba M, et al. Clinical and chest CT features as a predictive tool for COVID-19 clinical progress: introducing a novel semi-quantitative scoring system. Eur Radiol. 2021;31:11–11.
15. Yazdi NA, Ghadery AH, Seyedaliagahi SA, Jafari F, Jafari S, Hasannezad M, et al. Predictors of the chest CT score in COVID-19 patients: a cross-sectional study. Virol J. 2021;18(1):1–8.
16. Hall VG, Ferreira VH, Lerullo 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 Transpl. 2021;12:3980.

17. Fuerer V, Eviatar T, Zisman D, Peleg H, Paran D, Levartovsky D, et al. LB0003 Immunoengineer And Safety Of The BNT162b2 mRNA COVID-19 vaccine in adult patients with autoimmune inflammatory rheumatic diseases and general population: a multicenter study. BMJ. 2021.

18. Mehrabi Nejad MM, Moosaie F, Dehghanbanadaki H, Haji Ghadery A, Shabani M, Tabary M, et al. Immunoengineer of COVID-19 mRNA vaccines in immunocompromised patients: a systematic review and meta-analysis. Eur J Med Res. 2021;27:1–3.

19. Page MJ, McKenzie IE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, The PRISMA, et al. statement: an updated guideline for reporting systematic reviews. BMJ. 2020;2021.

20. National Heart L, Institute B. Study Quality Assessment Tools. https://www.nihbii.nih.gov/health-topics/study-quality-assessment-tools. Accessed 2019.

21. Egger M, Smith GD, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997;315(709):629–34.

22. Borenstein M, Hedges LV, Higgins JP, Rothstein HR. A basic introduction to fixed-effect and random-effects models for meta-analysis. Res Synth Methods. 2010;1(2):97–111.

23. Addeo A, Shah PK, Bordry N, Hudson RD, Bordy N, Hudson RD, Albracht B, D Marco, et al. Immunogenicity of SARS-CoV-2 messenger RNA vaccines in patients with cancer. Cancer Cell. 2021;39(8):1091–8.e2.

24. 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. JASN. 2021;32:2147.

25. Boekel L, Steenhuys M, Hooijberg F, Besten YR, van Kempen ZLE, Kummer LV, 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;3:e778.

26. Chevallier P, Coste-Burel M, Le Bourgeois A, Peterlin P, Garnier A, Béné MC, et al. Safety and immunogenicity of a first dose of SARS-CoV-2 mRNA vaccine in allogeneic hematopoietic stem-cells recipients. EJHaem. 2021;2:520.

27. Danthu C, Hantz S, Dahlem A, Duval M, B a B,Guiibert M, et al. Humoral response after SARS-CoV-2 mRNA vaccination in a cohort of hemodialysis patients and kidney transplant recipients. J Am Soc Nephrol. JASN. 2021;32:2153.

28. Del Bello A, Abravanel F, Marion O, Couat C, Esposito L, Lavayssière L, et al. Immunogenicity of SARS-CoV-2 messenger RNA-1273 vaccine in patients undergoing treatment for cancer. JAMA Oncol. 2021;7:1507.

29. Easdale S, Shea R, Ellis L, Bazin J, Davis K, Dallas F, et al. Serologic status and toxic effects of the SARS-CoV-2 BNT162b2 vaccine in patients undergoing treatment for cancer. JAMA Oncol. 2021;7:1507.

30. Firket L, Descy J, Seidel L, Bonvoisin C, Bouquegneau A, Grosch S, et al. Immunogenicity of the BNT162b2 mRNA vaccine in heart transplant recipients after two doses of an mRNA Covid-19 vaccine in transplant recipients. Clin Infect Dis Off Publ Infect Dis Soc Am. 2021;7:1093.

31. Ghandili S, Schoenlein M, Luetgehetmann M, Zur Wiesch JS, Becher J, Prendecki M, Clarke C, Edwards H, McIntyre S, Mortimer P, Gleeson SG, 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.

32. Monin L, Laing AG, Munoz-Ruiz M, McKenzie DR, Del Barrio ID, Alagathurthi 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(6):765–78.

33. Palich R, Veyni M, Marot S, Vozy A, Gligorov J, Maingon P, et al. Weak humoral and cellular immune response after a single dose of SARS-CoV-2 mRNA vaccine in treated cancer patients. Ann Oncol Off J Eur Soc Med Oncol. 2021;32(8):1051–3.

34. 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(11):81.

35. Perndecki 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.

36. 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;16:251.

37. Schramm R, Costard-Jackle A, Rivinius R, Fischer B, Muller 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(8):1-9.

38. Strauss AT, Hallott 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 Off Publ Am Assoc Study Liver Dis Int Liver Transplant Soc. 2021;27:1852.

39. Terpos E, Gaviatopoulou M, Tanasias-Stathopoulos I, Biasoulis 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(8):1.

40. Terpos E, Zagouri F, Lioni M, Skirou AD, Koutsoukos K, Markellos C, et al. Low titers of SARS-CoV-2 neutralizing antibodies after first vaccination dose in cancer patients receiving checkpoint inhibitors. J Hematol Oncol. 2021;14(1):66.

41. Thakkar A, Gonzalez-Lugo JD, Goradia N, Gali R, Shapiro LC, Pradhan K, et al. Serum conversion rates following COVID-19 vaccination among patients with cancer. Cancer Cell. 2021;39(8):1081-90.e2.
