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SHORT REPORT

Cancer Epidemiology

Antibody response to three-dose anti-SARS-CoV-2 mRNA-vaccination in treated solid cancer patients

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Abstract

Solid cancer patients are at higher risk of SARS-CoV-2 infection and severe complications. Moreover, vaccine-induced antibody response is impaired in patients on anticancer treatment. In this retrospective, observational, hypothesis-generating, cohort study, we assessed the antibody response to the third dose of mRNA vaccine in a convenience sample of patients on anticancer treatment, comparing it to that of the primary two-dose cycle. Among 99 patients included, 62.6% were ≥60 years old, 32.3% males, 67.7% with advanced disease. Exactly 40.4% were receiving biological therapy, 16.2% chemotherapy only and 7.1% both treatments. After the third dose, seroconversion rate seems to increase significantly, especially in non-responders to two doses. Heterologous vaccine-type regimen (two-dose mRNA-1273 and subsequent tozinameran or vice versa) results in higher antibody levels. This explorative study suggests that repeated doses of mRNA-vaccines could be associated with a better antibody response in this population. Furthermore, heterologous vaccine-type three-dose vaccination seems more effective in this population. Since this is a hypothesis-generating study, adequately statistically powered studies should validate these results.

KEYWORDS
cancer, COVID-19, immunogenicity, third dose, vaccine

What's new?

People with cancer have a higher risk of SARS-CoV-2 infection and severe complications, and cancer treatments can reduce the protective effect of vaccines. Here, the authors tested the antibody response to the third dose of mRNA vaccine in 99 patients undergoing treatment for

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cancer. They found that the third dose stimulated antibody production in nearly all the patients, including those who failed to produce antibodies after the first two doses. Varying the vaccine type for the third dose, from tozinameran to mRNA-1273 or vice versa, increased the antibody response.

1 | INTRODUCTION

Cancer patients are particularly susceptible to SARS-CoV-2 infection and COVID-19 complications and, therefore, have an increased lethality rate.[1] Immunocompromised patients were excluded from COVID-19 vaccine trials. Thus, since the approval of novel mRNA-vaccines, observational studies were conducted in cancer patients to assess vaccine immunogenicity and efficacy.[2]

To date, few studies compared the seroconversion rates after a two-dose cycle to the rate after booster dose of mRNA-vaccines in a population of treated solid cancer patients.[3–8] We previously reported that the seroconversion rate after the primary two-dose regimen was impaired in treated cancer patients except for previously virus-exposed subjects.[9] In this study, we evaluated the immunogenicity of heterologous and homologous vaccine-type three-dose mRNA-vaccination in the same population, focusing on two-dose non-responders and subjects receiving chemotherapy.

2 | METHODS

This is a retrospective, single-center, observational study based on a convenience sample of patients receiving treatment for solid cancer that was conducted at the Luigi Sacco Hospital in Milan, Italy, between March 2021 and April 2022. The study followed the "Strengthening the Reporting of Observational Studies in Epidemiology" (STROBE) guidelines for cohort studies. The Luigi Sacco Hospital is a secondary referral center. We recruited subjects who attended our outpatient clinic only. We proposed patients to adhere to the study during routine visits. Blood samples were collected at the time of the visit.

Cancer treatment was defined as an ongoing anticancer medical therapy, or an anticancer medical treatment received within the previous 12 months. Obesity was defined as body mass index (BMI) of at least 30. Comorbidity was defined as the presence of at least one relevant disease other than cancer. Hematological malignancies and HIV-positivity were exclusion criteria as known causes of immune depression. All data were retrospectively collected in a standardized format, including cancer diagnosis, cancer stage, anticancer therapy, and clinical features before vaccination. Sex was classified as male or female since all patients considered themselves to belong to only one of the two prespecified gender categories. Data on race and ethnicity were excluded from the analysis since more than 95% of the population was Caucasian. All patients received the primary two-dose cycle of tozinameran or mRNA-1273 following drug-specific recommendations and the third dose was administered not earlier than 4 months after the second dose. The primary two-dose cycle was administered before starting anticancer therapy or on the first day of the treatment cycle. SARS-CoV-2 antibody testing was performed before (pre-V1), 30 days after (post-V2) the primary cycle and 30 days after the booster dose (post-V3). Heterologous vaccine-type regimen was defined as the use of different mRNA vaccine types as primary two-dose cycle and booster dose (primary tozinameran and booster mRNA-1273 or vice versa).

2.1 | Serological parameters evaluation

We used an FDA-approved fluorescence bead-based multiplex assay (Luminex xMAP®, Luminex Corp.) to assess serum titer of anti-SARS-CoV-2 immunoglobulin G (IgG). The assay identifies IgGs directed to spike protein (S1), receptor-binding domain (RBD) and nucleo-capsid (N) of SARS-CoV-2. The data were analyzed using xMAP- MULTI-IgG-CoV-2 Assay Software (Luminex Corp., Austin, Texas). Threshold values for N, S1 and RBD were set to 700 median fluorescence intensity (MFI) for all three antigens and 300 for the background, as per manufacturer specifications.

2.2 | Statistical analysis

Analyses were performed using the R statistical software, version 4.0.2 (R Foundation for Statistical Computing). Median and interquartile range (IQR) was used to describe anti-S1 and anti-RBD levels across groups defined by socio-demographics, clinical features, and information related to the vaccination. Wilcoxon Rank Sum Test or the Kruskal–Wallis Rank Sum Test was used to compare anti-S1 and anti-RBD across groups. Subgroups analysis was conducted using the median and interquartile range (IQR). Multivariate analyses were conducted using median regression with anti-S1 and anti-RBD as dependent variables in separate models. The significance threshold was set at $P < .05$.

3 | RESULTS

We enrolled 99 consecutive patients. Considering the major risk factors for reduced antibody response, we report that 62.6% were ≥60 years old, 32.3% were males, 67.7% were in advanced stage of disease and 14.1% were on treatment for lung cancer.

To stratify the iatrogenic risk of infection, we report that the 40.4% of subjects were receiving biological therapy (immunotherapy,

cyclin-dependent kinase 4/6 inhibitors, tyrosine-kinase inhibitors and monoclonal antibodies), 16.2% were receiving chemotherapy only and 7.1% a combination of both treatments. The 30.4% of the patient population on chemotherapy were treated with a regimen at intermediate-high risk of febrile neutropenia.

Only in a minority of patients (30.4%) the third dose was injected within 48 hours from the oncologic therapy cycle. Finally, a heterologous vaccine regimen was administered in 25.3% of the subjects. One primary-vaccination non-responder patient developed COVID-19 between the second and the third dose. For complete demographic and clinical characteristics of cancer patients, see Table S1.

Seroconversion after the third dose was reached in 99% of individuals. Antibody levels at post-V3: anti-RBD IgG mean level [min, max] 18,419 [35, 24,270] MFI; anti-S1 IgG mean level [min, max] 10,289 [29, 17,813] MFI (Figure 1). After the primary vaccination, 22 patients had failed to seroconvert. Among them, 21 seroconverted after the third dose (anti-S1 IgG mean level 8491 [IQR 4652, 12,567] MFI at post-V3) (Figure 1A). For a better comparison, mean antibody levels at post-V2: anti-RBD IgG mean level 13,902 MFI; anti-S1 IgG mean level 2806 MFI. Among primary cycle non-responders: at post-V2, anti-RBD IgG mean level 87 MFI, anti-S1 IgG mean level 330 MFI; at post-V3, anti-RBD IgG mean level 10,589 MFI, anti-S1 IgG mean level 8491 MFI. In primary vaccination responders: at post-V2, anti-RBD IgG mean level 14,334 MFI, anti-S1 IgG mean level 3514 MFI; at post-V3, anti-RBD IgG mean level 18,664 MFI, anti-S1 IgG mean level 10,803 MFI.

Univariate analyses reported that antibody levels after the third dose were independent from age, gender, BMI, comorbidities, cancer stage, cancer treatment, neutropenic potential of chemotherapy, previous viral exposure, timing of third dose and third dose vaccine type. Breast cancer ($P = .01$) and granulocyte colony stimulating factor (G-CSF) administration ($P = .039$) reduced the 3rd-dose anti-RBD

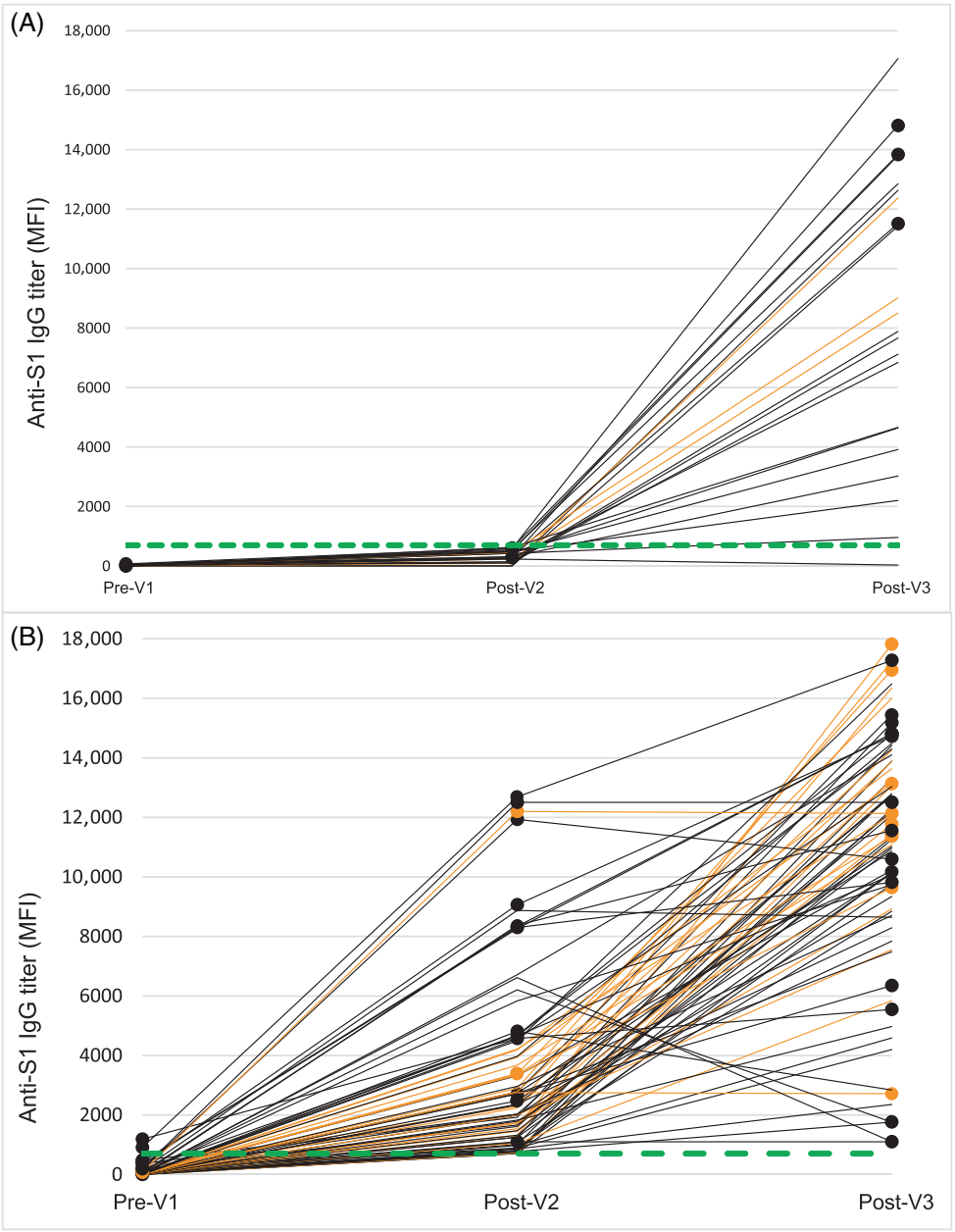

FIGURE 1 Change in anti-S1 IgG levels at the three time points in non-responders (A) and in responders (B) to the primary vaccination regimen. Black dots or orange dots: Anti-N1 ≥700 MFI. Black line: homologous regimen. Green dotted line: threshold for seroconversion. MFI, median fluorescence intensity. Orange line: heterologous regimen. Post-V3: after booster dose. Pre-V1: before primary vaccination cycle, Post-V2: after primary vaccination cycle.

TABLE 1 Patient variables associated with anti-S and anti-RBD IgG Ab level after the third vaccine dose.

Antibody level at post-V3	Anti-S1 post-V3 [median (IQR)]	*P*-value	Anti-RBD post-V3 [median (IQR)]	*P*-value
Age		.27		.07
<60 years	10,589 (5845, 12,783)		19,364 (14,536, 21,568)	
≥60 years	11,349 (8595, 13,753)		20,896 (17,028, 22,394)	
BMI		.85		.24
Underweight	13,130 (n/a, n/a)		22,644 (n/a, n/a)	
Normal	11,169 (7807, 13,220)		20,910 (17,967, 21,857)	
Overweight	11,019 (7124, 13,630)		19,081 (15,038, 21,575)	
Obesity I	11,555 (9974, 14,341)		21,895 (19,487, 22,628)	
Obesity II	10,346 (7446, 11,854)		15,716 (13,940, 18,490)	
Obesity III	10,450 (9147, 11,753)		19,733 (18,204, 21,263)	
Gender		.16		.07
M	11,812 (9515, 14,437)		20,957 (18,443, 22,496)	
F	10,589 (7523, 13,093)		19,601 (15,084, 21,868)	
Tumor site		.87		**.03**
Breast	11,257 (6349, 13,130)		18,039 (14,482, 21,575)	
Lung	11,019 (10,148, 14,307)		20,331 (18,163, 21,675)	
Gastroenteric	11,555 (8511, 14,420)		21,379 (19,081, 22,206)	
Genitourinary	11,155 (7629, 12,736)		21,772 (19,351, 22,891)	
Gynecologic	10,497 (8321, 12,802)		22,460 (21,392, 23,039)	
Treatment		.24		.29
Last treatment administered ≥12 months before	12,082 (11,274, 13,160)		21,554 (19,816, 22,240)	
Chemotherapy	5697 (2808, 13,819)		17,225 (11,496, 21,855)	
Target therapy	11,391 (8131, 13,170)		21,288 (16,379, 22,326)	
Chemotherapy + target therapy	11,019 (9384, 13,348)		19,911 (16,760, 20,788)	
Last treatment administered ≤12 months before	12,855 (9345, 14,488)		20,470 (18,039, 21,575)	
Hormonal therapy	10,128 (7817, 11,963)		19,138 (14,374, 20,817)	
Steroids		.50		.51
No	11,298 (7879, 13,671)		20,263 (15,484, 21,973)	
Yes	8849 (5886, 13,003)		19,745 (18,436, 22,962)	
Comorbidity		.72		.75
0	10,220 (7577, 13,542)		20,452 (15,398, 21,899)	
1	11,393 (8272, 13,200)		20,109 (16,188, 21,875)	
≥2	11,951 (8901, 13,414)		19,710 (17,951, 22,377)	
Vaccine type		.20		.99
mRNA-1273	12,370 (9751, 13,895)		20,331 (16,674, 21,904)	
Tozinameran	11,050 (7232, 12,986)		19,828 (15,562, 22,062)	
Vaccination regimen		**.04**		.51
Homologous	10,405 (6913, 12,986)		20,461 (16,072, 22,031)	
Heterologous	12,128 (9642, 13,873)		19,138 (15,493, 22,062)	

Note: Bold values mean to highlight $P < .05$.
Abbreviations: BMI, body mass index; G-CSF, granulocyte-colony stimulating factor; IQR, interquartile range; post-V3: 28 days after third dose.

response, but multivariate analysis could not be performed due to the small sample size. A homologous vaccine-type scheme was significantly associated to lower anti-S1 IgG levels ($P = .04$) (Table 1). In this regard, in multivariate analysis, a primary cycle with mRNA-1273 and tozinameran as booster dose was significantly associated with increased anti-S1 levels (vs homologous, $P = .01$; vs primary tozinameran/booster mRNA-1273, $P = .001$) (Table 1, Figure 1B). To favor the interpretation of the main results of this study, in Figure 1 we reported anti-S1 IgG levels only, since anti-RBD IgG levels did not demonstrate as statistically significant in multivariate analyses.

A further analysis showed that non-responders to primary vaccination had a higher increase in their relative amount of anti-S1 and anti-RBD IgG after the third dose if compared to the responder group. The difference in the antibody percentage after the primary cycle and after the booster (antibody, mean [min, max] in non-responder vs responder) was anti-S1, 2560 [901, 5159] vs 277 [126, 645]; anti-RBD, 278 [151, 544] vs 11 [−7, 55] ($P < .0001$). The higher increase in antibody titers in two-dose non-responders was independent from a previous exposure to the virus (anti-S1, $P < .001$; anti-RBD, P .003) or a switch to a less immunosuppressive type of anticancer therapy (anti-S1, P .004; anti-RBD, P .005).

4 | DISCUSSION

The third dose of mRNA-vaccines seemed to be immunogenic in most of the patients, including subjects who failed to seroconvert after the two-dose primary cycle. The substantial increase in the immune response of primary cycle non-responders could be solely attributable to the effect of the booster dose. At the explorative analysis, none of the considered factors seemed to affect the levels of antibody production except for the use of a heterologous vaccine-type regimen.

To date, few studies reported antibody response to three-dose mRNA-vaccination in treated solid cancer patients using both tozinameran and mRNA-1273.[4,5] Considering the results of this explorative study, we hypothesize that a heterologous vaccine-type mRNA-vaccination regimen could enhance the antibody response of treated solid cancer patients compared to a homologous one, as previously reported in the general population.[10] This study has limitations. First, the test used was set for the assessment of primary vaccination response. In the literature, antibody levels demonstrated to be significantly higher after the booster dose, if compared to the primary two-dose vaccine cycle, in cancer patients. Indeed, seroconversion rate could have been overestimated due to an abnormally low threshold. Moreover, the more prominent methodological weakness is that the study is retrospective and based on a convenience sample; therefore, it is powered to be hypothesis-generating only. Furthermore, the sample size was believed to be sufficient to allow meaningful analysis; however, the study may not be powered enough to evaluate associations within subgroups due to a limited sample size. In addition, major limitations are, first, the absence of the evaluation of cell-mediated immunity and the antibody neutralizing capacity against new SARS-CoV-2 VOCs (Variants of Concern). However, since anti-S1 IgG levels can be considered as a surrogate of the breadth of neutralization against variants,[11] we report that 20E (EU1), Alfa (B.1.1.7 and B.1.1.7 + E484K), Delta (B.1.617.2, 21K and 21J) and Omicron (BA.1) were circulating in Italy in the study period.[12] Another limitation is the absence of follow-up data about the waning of antibody response after the third dose. Finally, this study lacked a control cohort. Considering historical data in healthy individuals, antibody response to the third dose seems similar compared to cancer patients.[13]

This study could expand the knowledge regarding the immune-stimulation capacity of mRNA vaccines in cancer patients. These informations could be important in the future development of mRNA-based antitumor vaccines. Our study suggests the possibility of enhancing the immune stimulation with the use of different types of mRNA-based antitumor vaccines within the same therapeutic course. These findings could support the design of new experimental studies testing the efficacy of antitumor vaccines. Since our study included patients with a previous SARS-CoV-2 infection, the data reported could provide additional informations regarding "hybrid immunity." This could be an immunological phenomenon of particular relevance in the study of the antitumor immunity, since the immune system of cancer patients has been exposed to tumor antigens in a manner that is similar to what occurs with SARS-CoV-2 antigens in individuals with a previous exposure to the virus.[14]

In this observational, explorative study of patients treated with anticancer therapy, the third SARS-CoV-2 mRNA vaccine dose appeared to induce an antibody response in previously non-responders. The small sample size could have hampered the evaluation of possible predictors of response. Heterologous vaccine-type mRNA vaccination seemed to enhance the humoral immune response compared to homologous vaccination. However, since the design of this study is powered to be hypothesis-generating only, prospective and larger studies are needed to validate these results.

AUTHOR CONTRIBUTIONS

Davide Dalu: Concept and design; Acquisition, analysis, or interpretation of data; Drafting of the article; Supervision. **Maciej Tarkowski:** Concept and design; Acquisition, analysis, or interpretation of data. **Lorenzo Ruggieri:** Concept and design; Acquisition, analysis, or interpretation of data; Drafting of the article. **Maria Silvia Cona:** Concept and design; Acquisition, analysis, or interpretation of data; Critical revision of the article for important intellectual content. **Arianna Gabrieli:** Concept and design; Acquisition, analysis, or interpretation of data. **Davide De Francesco:** Statistical analysis. **Cinzia Fasola:** Administrative, technical, or material support. **Sabrina Ferrario:** Administrative, technical, or material support. **Anna Gambaro:** Administrative, technical, or material support. **Elsa Masedu:** Drafting of the article; Administrative, technical, or material support. **Gaia Parma:** Administrative, technical, or material support. **Eliana Rulli:** Critical revision of the article for important intellectual content. **Claudia De Stradis:** Acquisition, analysis, or interpretation of data. **Domenico Mavilio:** Administrative, technical, or material support. **Francesca Calcaterra:** Administrative, technical, or material support. **Federica Manoni:** Administrative, technical, or material support. **Agostino Riva:** Concept and design; Acquisition, analysis, or interpretation of data; Critical revision of the article for important intellectual content; Obtained funding; Supervision. **Nicla La Verde:** Concept and design; Acquisition, analysis, or interpretation of data; Drafting of the article; Supervision. The work reported in the article has been performed by the authors, unless clearly specified in the text.

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CONFLICT OF INTEREST STATEMENT

Nicla La Verde reports grant as consulting or advisory role: Novartis, Pfizer, Roche, MSD, Astrazeneca; speaker bureau: GSK, Pfizer, Roche, Gentili, Lilly, Daiichi-Sankyo; travel expenses: Pfizer, Roche; research funding: EISAI. Davide Dalu reports receiving grants from Gentili, travel expenses from Roche, Gentili, Eisai. Lorenzo Ruggieri reports speaker bureau from AstraZeneca. The other authors have no financial conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

Data are available upon request to the corresponding author.

ETHICS STATEMENT

The study had been previously approved by the "Milano Area 1 Ethics Committee." The study protocol was approved by the Istituto Spallanzani Ethical Committee and AIFA (number 312 of the experimental registry 2020/2021) and conducted according to the principles of the Declaration of Helsinki. All the participants signed written informed consent before any study procedure. Participants did not receive any financial compensation. All subject data were anonymized as required by the Italian Data Protection Code (Legislative Decree 196/2003) and the general authorizations issued by the Italian Data Protection Authority.

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REFERENCES

1. Williamson EJ, Walker AJ, Bhaskaran K, et al. Factors associated with COVID-19-related death using OpenSAFELY. *Nature*. 2020;584:430-436.
2. Fendler A, de Vries EGE, GeurtsvanKessel CH, et al. COVID-19 vaccines in patients with cancer: immunogenicity, efficacy and safety. *Nat Rev Clin Oncol*. 2022;19:385-401.
3. Fenioux C, Teixeira L, Fourati S, et al. SARS-CoV-2 antibody response to 2 or 3 doses of the BNT162b2 vaccine in patients treated with anticancer agents. *JAMA Oncol*. 2022;8:612-617.
4. Su E, Fischer S, Demmer-Steingruber R, et al. Humoral and cellular responses to mRNA-based COVID-19 booster vaccinations in patients with solid neoplasms under active treatment. *ESMO Open*. 2022;7:100587.
5. Shapiro LC, Thakkar A, Campbell ST, et al. Efficacy of booster doses in augmenting waning immune responses to COVID-19 vaccine in patients with cancer. *Cancer Cell*. 2022;40:3-5.
6. Nelli F, Giannarelli D, Fabbri A, et al. Immunogenicity and early clinical outcome after two or three doses of SARS-CoV-2 mRNA-BNT162b2 vaccine in actively treated cancer patients: results from the prospective observational Vax-On-Third study. *Ann Oncol*. 2022;33:740-742.
7. Oosting SF, van der Veldt AAM, Fehrmann RSN, et al. Immunogenicity after second and third mRNA-1273 vaccination doses in patients receiving chemotherapy, immunotherapy, or both for solid tumours. *Lancet Oncol*. 2022;23:833-835.
8. Noia VD, Pimpinelli F, Renna D, et al. Potentiation of humoral response to the BNT162b2 vaccine after the third dose in patients with solid cancer. *Ann Oncol*. 2022;33:563-565.
9. La Verde N, Riva A, Cona MS, et al. Immunogenicity of two doses of BNT162b2 and mRNA-1273 vaccines for solid cancer patients on treatment with or without a previous SARS-CoV-2 infection. *Int J Cancer*. 2022;152:661-671.
10. Atmar RL, Lyke KE, Deming ME, et al. Homologous and heterologous Covid-19 booster vaccinations. *N Engl J Med*. 2022;386:1046-1057.
11. Naranbhai V, St Denis KJ, Lam EC, et al. Neutralization breadth of SARS-CoV-2 viral variants following primary series and booster SARS-CoV-2 vaccines in patients with cancer. *Cancer Cell*. 2022;40:103-108.
12. EpiCentro. Monitoraggio delle varianti del virus SARS-CoV-2 di interesse in sanità pubblica in Italia [Internet]. https://www.epicentro.iss.it/coronavirus/sars-cov-2-monitoraggio-varianti-rapporti-periodici. Accessed October 27, 2022
13. Moore SC, Kronsteiner B, Longet S, et al. Evolution of long-term vaccine-induced and hybrid immunity in healthcare workers after different COVID-19 vaccine regimens. *Med*. 2023;4:191-215.
14. Meo C, Palma G, Bruzzese F, Budillon A, Napoli C, de Nigris F. Spontaneous cancer remission after COVID-19: insights from the pandemic and their relevance for cancer treatment. *J Transl Med*. 2023;21:273.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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