Boosting of the SARS-CoV-2–Specific Immune Response after Vaccination with Single-Dose Sputnik Light Vaccine

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Despite measures taken world-wide, the coronavirus disease 2019 (COVID-19) pandemic continues. Because efficient antiviral drugs are not yet widely available, vaccination is the best option to control the infection rate. Although this option is obvious in the case of COVID-19–naive individuals, it is still unclear when individuals who have recovered from a previous SARS-CoV-2 infection should be vaccinated and whether the vaccination raises immune responses against the coronavirus and its novel variants. In this study, we collected peripheral blood from 84 healthy human donors of different COVID-19 status who were vaccinated with the Sputnik Light vaccine and measured the dynamics of the Ab and T cell responses, as well as the virus-neutralizing activity (VNA) in serum, against two SARS-CoV-2 variants, B.1.1.1 and B.1.617.2. We showed that vaccination of individuals previously exposed to the virus considerably boosts the existing immune response. In these individuals, receptor-binding domain (RBD)–specific IgG titers and VNA in serum were already elevated on the 7th day after vaccination, whereas COVID-19–naive individuals developed the Ab response and VNA mainly 21 d postvaccination. Additionally, we found a strong correlation between RBD-specific IgG titers and VNA in serum, and according to these data vaccination may be recommended when the RBD-specific IgG titers drop to 142.7 binding Ab units/ml or below. In summary, the results of the study demonstrate that vaccination is beneficial for both COVID-19–naive and recovered individuals, especially since it raises serum VNA against the B.1.617.2 variant, one of the five SARS-CoV-2 variants of concern. The Journal of Immunology, 2022, 208: 1139–1145.

Materials and Methods

Ethics

This study was approved by the Moscow City Ethics Committee of the Research Institute of the Organization of Health and Healthcare Management and performed according to the Helsinki Declaration. All participants provided their written informed consent. This study is a part of a project that has been registered on ClinicalTrials.gov (identifier NCT04898140). After providing written informed consent, the individuals hand-filled a questionnaire containing information about their demographics, health, marital and reproductive status, medical history, and other relevant information.

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Abbreviations used in this article: BAU, binding Ab unit; COVID-19, coronavirus disease 2019; M protein, membrane protein; N protein, nucleocapsid protein; RBD, receptor-binding domain; ROC, receiver operating characteristic; RT, room temperature; S protein, spike protein; VNA, virus-neutralizing activity.

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Blood collection and PBMC isolation
Peripheral blood was collected into two 8-ml BD Vacutainer CPT tubes with sodium citrate (BD Biosciences) and was processed within 2 h after venipuncture. We isolated PBMCs according to the manufacturer’s standard protocol by centrifugation at 1800–2000 × g for 20 min with slow brake at room temperature (RT). After centrifugation, PBMCs were collected into a 15-ml conical tube, washed twice with PBS (PanEco, Moscow, Russia) with EDTA at 2 mM (PanEco), counted, and used for an IFN-γ ELISPOT assay. PBMCs with a viability level ≥70% were taken into the study. For serum isolation, peripheral blood was collected into S-Monovette 7.5-ml Z tubes (Sarstedt, Nümbrecht, Germany).

SARS-CoV-2–specific Abs and VNA in serum
We analyzed titers of the IgGs specific to the receptor-binding domain (RBD) of the SARS-CoV-2 S protein in serum using the automated Architect i1000SR analyzer with compatible reagent kit (Abbott, Abbott Park, IL) according to the manufacturer’s standard protocol. The RBD sequence used was taken from the complete genome sequence of SARS-CoV-2 isolate Wuhan-Hu-1 (GenBank: MN908947.3; https://www.ncbi.nlm.nih.gov/nucleotide/MN908947.3). Values obtained were recalculated in binding Ab units (BAU)/ml in accordance with the World Health Organization international standard (9); the IgG value equal to 7.2 BAU/ml was used as a seropositivity cutoff according to the manufacturer’s instructions. We evaluated the VNA in serum from a microneutralization assay using the B.1.1.1 [PMVL-1 (GISAID EPI_ISL_421275)] and B.1.617.2 (T19R GI42D E156G F157del R158del L452R T478K D614G P681R D950N) SARS-CoV-2 variants in a 96-well plate and a 50% tissue culture-infective dose of S-CoV-2 variants in a 96-well plate and a 50% tissue culture-infective dose of S-CoV-2. Titers of the IgGs specific to the receptor-binding domain (RBD) of the SARS-CoV-2 were estimated at the indicated days postvaccination and represented as standard box-and-whiskers diagrams with individual values represented by dots. NoS, number of spots estimated from ELISPOT (see Materials and Methods for details). **1 × 10⁻³ < p ≤ 1 × 10⁻², ****p ≤ 1 × 10⁻⁴, ns (not significant), 5 × 10⁻² ≤ p.

FIGURE 1. Dynamics of the Ab and T cell responses. (A and B) Titers of the IgGs specific to the receptor-binding domain (RBD) of the SARS-CoV-2 spike (S) protein (A) and frequencies of the S protein–specific T cells in peripheral blood (B) were estimated at the indicated days postvaccination and represented as standard box-and-whiskers diagrams with individual values represented by dots. NoS, number of spots estimated from ELISPOT (see Materials and Methods for details). **1 × 10⁻³ < p ≤ 1 × 10⁻², ****p ≤ 1 × 10⁻⁴, ns (not significant), 5 × 10⁻² ≤ p.
of ≥20 and <20 for either B.1.1.1 or B.1.617.2 using RBD-specific IgG titers as a single-input parameter was built, and corresponding receiver operating characteristic (ROC) curves were used for selection of optimal thresholds. The ROC curve is a graphical plot that shows the changes in a binary classifier to discriminate between different groups with a change in a discriminating threshold. For each value of a threshold (i.e., RBD-specific IgG titer level) the true positive rate (or sensitivity) is plotted against the false positive rate (equals 1 – specificity), allowing researchers to find the threshold that is optimal in terms of the desired balance between sensitivity and specificity.

Results

Cohort characteristics

A total of 84 initially non-vaccinated Moscow residents were included in the study (Table I). In the course of the study, participants were vaccinated with Sputnik Light vaccine and their blood was collected prior to the vaccination, as well as on days 7 and 21 after vaccine administration.

Changes in Ab and T cell response levels

Serological testing of the participants on the day of their inclusion in the study revealed that 44 (52.4%) individuals were seropositive for the virus-specific IgGs (Fig. 1A). Among them, 36 (81.8%) individuals also demonstrated the presence of SARS-CoV-2-specific T cells in peripheral blood (Fig. 1B). These data, taken together with the self-reported COVID-19 cases in this group, indicated that these individuals had been previously exposed to SARS-CoV-2.

Within the observational period among the cohort, there was a constant increase in the titers of IgGs specific to the RBD of the coronavirus S protein (Fig. 1A). Accordingly, the fraction of seropositive individuals also increased from 52.4 to 57.1% on the 7th day, and to 100% on the 21st day postvaccination. The results of the IFN-γ ELISPOT demonstrated that the T cell response developed faster than did the Ab one. Frequencies of peripheral blood T cells specific to coronavirus S protein had already increased on the 7th day postvaccination.

FIGURE 2. Characteristics of the different clusters of participants. (A–D) For each cluster, receptor-binding domain (RBD)-specific IgG titers (A), frequencies of S protein–specific T cells (B), and virus-neutralizing activity (VNA) in serum against B.1.1.1 (C) and B.1.617.2 (D) SARS-CoV-2 variants were estimated as described in the Materials and Methods section and represented as standard box-and-whisker diagrams with individual values represented by dots. Orange corresponds to cluster 1, green to cluster 2, red to cluster 3. NoS, number of spots estimated from ELISPOT.
FIGURE 3. Analysis of the virus-neutralizing activity in serum against B.1.1.1 and B.1.617.2 SARS-CoV-2 variants. (A) Dot plots for comparison between virus-neutralizing activity (VNA) in serum against B.1.1.1 and against B.1.617.2 for all patients at all time points. (B) Boxplots for ratio of VNA against B.1.1.1 to VNA against B.1.617.2 for all patients at different time points with both VNA against B.1.1.1 and VNA against B.1.617.2 above 0. (C) Left, Dot plot for pairwise comparisons of RBD-specific IgG titers and VNA against B.1.1.1 for all patients at all time points; the zone (Figure legend continues)
and did not change significantly on the 21st day (Fig. 1B), with the fractions of individuals positive for the T cell response being 36.1, 86.6, and 96.4% on days 0, 7, and 21 postvaccination, respectively. Meanwhile, throughout the observation period, the fractions of peripheral blood T cells specific to membrane (M) and nucleocapsid (N) SARS-CoV-2 proteins showed no statistically significant changes, nor did the fractions of individuals positive for M and N protein–specific T cell responses (Supplemental Fig. 1). These results were expected because the Sputnik Light vaccine provides for the expression of only S protein in human cells, and, therefore, it was unlikely that vaccination influenced N and M protein–specific T cells.

**Participant clusterization by the types of immune response dynamics**

To find the main patterns of the response to the vaccination, all participants were clustered according to the observed dynamics in RBD-specific IgG titers. For this purpose, we used the Ward variance minimization algorithm to discriminate these patterns in an unbiased way. Three clusters were identified (Fig. 2, Supplemental Fig. 2). Clusters 1 (n = 42) and 2 (n = 4) were composed of the individuals who were seropositive at the time of their inclusion in the study, except for two individuals from cluster 1 with IgG levels equal to 5.6 and 6.2 BAU/ml, which fall below the seropositivity cutoff of 7.2 BAU/ml according to the serological test manufacturer. Meanwhile, cluster 3 (n = 38) was composed of the seronegative individuals only, with the highest IgG level equal to 2.0 BAU/ml. No statistically significant differences between clusters in available clinical data were found.

All individuals from cluster 3 demonstrated no increase in IgG levels on day 7, but the titers were significantly elevated on day 21 postvaccination (Fig. 2A, Supplemental Fig. 3A). At the same time, we found a consistent increase in the frequencies of S protein–specific T cells throughout the observation period (Fig. 2B, Supplemental Fig. 3B).

Different results were observed in individuals previously exposed to SARS-CoV-2. Prior to the vaccination, clusters 1 and 2 were characterized by the same values of IgG titers and frequencies of S protein–specific T cells. However, in the case of cluster 1, IgG titers had already increased considerably on the 7th day postvaccination but were only slightly elevated on the 21st day. Frequencies of S protein–specific T cells in peripheral blood also increased considerably on day 7 postvaccination, but then dropped on the 21st day, reaching the same value as for cluster 3 (comprised of the SARS-CoV-2–naïve individuals).

In contrast to cluster 1, individuals in cluster 2 demonstrated no changes in either IgG titers or frequencies of S protein–specific T cells throughout the observation period. On the 21st day postvaccination, both parameters were significantly lower than those for individuals without previous SARS-CoV-2 exposure (cluster 3) (Fig. 2A, 2B, Supplemental Fig. 3A, 3B).

**Virus neutralizing activity in serum against different SARS-CoV-2 variants**

For a group of individuals from the cohort (47 participants), we analyzed the VNA in serum against two SARS-CoV-2 variants, B.1.1.1 and B.1.617.2. For this purpose, we used a microneutralization assay with different serum dilutions. Almost all individuals with previous SARS-CoV-2 exposure (those in clusters 1 and 2) demonstrated the presence of VNA against both variants even prior to the vaccination, with the values being indistinguishable (Fig. 2C, 2D, Supplemental Fig. 3C, 3D). Furthermore, in the case of cluster 1, VNA increased and reached the maximum already on the 7th day postvaccination, whereas VNA in serum of individuals in cluster 2 did not change for either virus variant until the end of the observation period. For SARS-CoV-2–naïve individuals from cluster 3, VNA in serum against both variants appeared mainly on the 21st day.

It is noteworthy that VNA values against both SARS-CoV-2 variants at each time point were proportional (Fig. 3A); however, VNA against the B.1.617.2 variant was approximately ~2-fold lower than that against the B.1.1.1 variant (Fig. 3B).

**Correlation between RBD-specific IgG titers and VNA in serum**

For each of the tested SARS-CoV-2 variants, we found a strong correlation between RBD-specific IgG titers and VNA in serum (Fig. 3C, 3D). Accordingly, these IgG titers can be potentially used as a predictor of the presence of VNA in serum. To test this ability, the results of serum VNA estimation were transformed into binary form. To minimize the impact of possible false-positive results on prediction, we set up the second serum dilution used in the study (20×; see Materials and Methods for details) as a threshold for the presence of VNA. For each SARS-CoV-2 variant, we generated and analyzed a corresponding ROC curve. Accordingly, the optimal sensitivity of the prediction was achieved at 19.4 and 23.3 BAU/ml for the B.1.1.1 and B.1.617.2 variants, respectively. This means that individuals with RBD-specific IgG titers lower than these values do not demonstrate the presence of VNA in serum. In contrast, the optimal specificity was achieved at a higher value, that is, 142.7 BAU/ml for both SARS-CoV-2 variants, thus indicating that IgG levels higher than this value reliably indicate the presence of serum VNA. However, when the RBD-specific IgG level fell in a range 19.4 (23.3)–142.7 BAU/ml, it was unable to predict reliably the presence of VNA.

Individuals having these IgG titers were characterized either by relatively low levels of serum VNA or by the absence of the neutralization activity.

**Discussion**

In the current study, we analyzed the effect of Sputnik Light vaccine administration on the anti-SARS-CoV-2 immune response in individuals of different COVID-19 status. For this purpose, we collected blood from participants prior to vaccination and at time points after vaccine administration. We analyzed the development of 1) IgGs specific to the RBD of the coronavirus S protein, 3) S protein–specific T cells in peripheral blood, and 3) VNA in serum against two SARS-CoV-2 variants, B.1.1.1 and B.1.617.2.

Upon vaccination with Sputnik Light, we observed different dynamics of both Ab and T cell responses depending on the previous SARS-CoV-2 infection status of the tested individuals. In accordance with published data (8), in COVID-19–naïve individuals, coronavirus-specific IgGs appeared largely on the 21st day postvaccination, and similar results were obtained for VNA against both coronavirus variants tested. In contrast, S protein–specific T cells had already appeared in peripheral blood on the 7th day, and their number further increased on the 21st day postvaccination. Meanwhile, already prior
to vaccine administration, 8 of 40 seronegative individuals were characterized by the presence of S protein–specific T cells, with 6 among them also testing positive for T cells specific to M and N proteins of SARS-CoV-2. The presence of SARS-CoV-2–specific T cells in these seronegative individuals might be explained by previously asymptomatic COVID-19, which has been shown to be associated with lack of Ab response or a rapidly decreasing one (11, 12), or these T cells might have developed as a result of a previous infection with the “common cold” coronaviruses and are cross-reactive to SARS-CoV-2 (13, 14).

As expected, individuals infected with SARS-CoV-2 prior to vaccination were already characterized by the presence of the SARS-CoV-2–specific IgGs and T cells, as well as of the VNA in serum, before the vaccination. For the vast majority of these individuals, all of these parameters had increased considerably on the 7th day postvaccination, thus indicating that for the recovered persons Sputnik Light served as an effective booster. However, among seropositive individuals four persons (11% of the seropositive group) did not respond to the vaccination with Sputnik Light, as evidenced by the lack of increase in anti–SARS-CoV-2 IgG titers, peripheral blood T cells, and VNA in serum. Although the reasons for this lack have yet to be understood, the fraction of non-responders is rather small and does not compromise the general efficacy of vaccination among COVID-19–recovered individuals.

Similar results were recently demonstrated for mRNA vaccines. Thus, in a number of studies it was shown that vaccination of individuals who recovered after COVID-19 with the Pfizer (BNT162b2) and Moderna (mRNA-1273) vaccines resulted in rapid induction of an anti–SARS-CoV-2 immune response (15–18). However, there is very limited information about the effectiveness of the application of adenovirus-based vaccines for immunization of COVID-19–recovered individuals. For ChAdOx1 nCoV-19, the single-dose adenovirus-vector vaccine from AstraZeneca, it was shown that the vaccine administered up to at least 11 mo after SARS-CoV-2 infection serves as an effective immune booster (19). A group from Argentina reported that a single Sputnik V dose elicits higher Ab levels and virus-neutralizing capacity in previously infected individuals than in naive ones receiving the full two-dose schedule (8). However, to date no such information is available for Johnson & Johnson’s Ad.26.COV2.S vaccine. Nevertheless, our results together with published ones indicate that adenovirus-based vaccines are a worthy option for reimmunization against COVID-19 along with mRNA vaccines.

Recent studies have shown that IgGs specific to the coronavirus S protein, particularly to its RBD portion, also demonstrate neutralizing activity against the virus (20–22). Similar results were obtained in our study: we found a strong correlation between RBD-specific IgG titers and VNA in serum. This correlation was especially pronounced in the study: we found a strong correlation between RBD-specific IgG titers and VNA in serum. Although the reasons for this lack have yet to be understood, the fraction of non-responders is rather small and does not compromise the general efficacy of vaccination among COVID-19–recovered individuals.

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Disclosures The authors have no financial conflicts of interest.

References
Figure S1. Dynamics of the T-cell response in the cohort. Frequencies of the peripheral blood T cells specific to M- (A) and N-protein (B) of SRAS-CoV-2 were estimated at the indicated days post vaccination and represented as standard box-and-whiskers diagrams with values represented by dots. NoS, number of spots estimated by ELISpot.
Figure S2. Clusterization of the participants by the dynamics of the antibody response. RBD-specific IgG titers were estimated as described in the Materials and Methods section and values were represented as a heatmap. Next, participants were clustered by the changes in the IgG titers using the Ward variance minimization algorithm. Clusters found are indicated as C1, C2, and C3.
Figure S3. Characteristics of the different clusters of participants. For each cluster, RBD-specific IgG titers (A), frequencies of S-protein–specific T cells (B), as well as virus neutralizing activity (VNA) in serum against B.1.1.1 (C) or B.1.617.2 (D) SARS-CoV-2 variants are shown. Values were obtained as described in the Materials and Methods section. For each panel, at left are boxplots for different clusters at indicated time points; orange corresponds to Cluster 1, green to Cluster 2, red to Cluster 3. At right are shown $p$-values for comparison between different clusters (Cluster, 1, 2, and 3 are designated as C1, C2, and C3, respectively) and/or different time points (0, 7, and 21 days post vaccination are designated as 0D, 7D, and 21D, respectively). For comparisons between different time points within same clusters, $p$-values from the Wilcoxon paired test are given; for comparisons between different clusters at the same time point, $p$-values from the Mann-Whitney test are given. We corrected all $p$-values corrected within each family of comparisons using the Benjamini-Hochberg method. Statistically significant differences ($p$-value < 0.05) are highlighted with purple. NoS, number of spots estimated by ELISpot.