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Short communication

Sustained superior humoral immune responses of mRNA vaccines compared to Sputnik V viral vector COVID-19 vaccines in naïve and convalescent populations

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ABSTRACT

Background: The choice of vaccine platform fundamentally influences the magnitude and durability of antibody responses against severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). We compared humoral immune responses between BNT162b2/mRNA-1273 (mRNA) and Sputnik V (adenoviral vector) vaccines across multiple timepoints.
Methods: Anti-ancestral (WT) spike binding antibodies were measured by enzyme-linked immunosorbent assay (ELISA) and neutralizing antibodies by microneutralization assay using live SARS-CoV-2 WA.1 strain. Sera from 48 naïve and 24 convalescent study participants were collected prior and after the primary immunization (mRNA: 28; Sputnik V: 44).
Results: mRNA vaccines elicited higher binding antibody responses ($p < 0.001$ in naïve, $p < 0.05$ in convalescent participants) and neutralizing antibody responses ($p < 0.001$ in naïve participants) compared to Sputnik V. Antibody decay kinetics were similar between platforms (half-life ~5 months), with mRNA vaccines maintaining sustained superiority through 6 months post-vaccination.
Conclusions: mRNA vaccination provides markedly superior and sustained antibody responses compared to adenoviral vector vaccine, which is particularly relevant for long-term protection strategies.

1. Introduction

The coronavirus disease-2019 (COVID-19) pandemic necessitated rapid development of diverse vaccine platforms, each with distinct immunological properties. While both mRNA and adenoviral vector vaccines demonstrate efficacy, fundamental differences in antigen presentation, cellular trafficking, and immune activation may result in divergent antibody kinetics [1,2]. Understanding these platform-specific differences is crucial for optimizing vaccination strategies, particularly regarding booster timing and hybrid immunity scenarios.

Previous studies have established that mRNA vaccines induce robust germinal center responses and affinity maturation [3,4], while adenoviral vectors may face limitations from pre-existing immunity and reduced antigen expression duration [5]. However, direct head-to-head comparisons of antibody durability between platforms remain limited, particularly in populations with varying baseline immunity.

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Understanding platform-specific durability differences is crucial for optimizing vaccination strategies. Here, we present a direct comparison of antibody responses to mRNA vaccines (BNT162b2 and mRNA-1273) and Sputnik V vaccines in both naïve and convalescent individuals, following responses from pre-vaccination through 180–200 days post-vaccination.

2. Methods

Study Design and Participants.

Samples leveraged for this study were received from the institutional review board (IRB) approved VIVA Clinical Core biorepository [STUDY-22-00077] for secondary analysis on human subject samples. The VIVA Clinical Core is reliant upon two IRB or local ethics reviewed and approved clinical observation research studies. The samples from naïve and convalescent individuals who received the complete, two-dose primary series of Sputnik V (rAd26-S followed by rAd5-S) were sourced from the Biobank of Infectios Diseases in Argentina (Biobanco de Enfermedades Infecciosas), which is approved through the Fundación Huesped Comite de Bioetica (Bioethics Committee). Samples from naïve and convalescent individuals who received two doses of an mRNA vaccine as their primary immunization were sourced through the Protection Associated with Rapid Immune Response to SARS-CoV-2 (PARIS) [STUDY-20-00442]. Samples were obtained at time points prior to vaccination, between dose 1 and dose 2 (inter-dose), peak post-dose 2, 120 days, and long-term timepoints. All participants received their primary series according to manufacturer recommendations: BNT162b2 recipients received doses 21 days apart, mRNA-1273 recipients received doses 28 days apart, and Sputnik V recipients received doses 21 days apart. The inter-dose timepoint samples (collected at day 15 post-first dose) were obtained prior to second dose administration for all participants. All participants provided informed consent and clinical metadata in addition to biospecimen for future use by the respective biorepositories, coordinated by the VIVA Clinical Core. The participant samples selected from the biorepositories were chosen based on the availability of longitudinal serum collected at the specified timepoints (pre-vaccination through 180–200 days) and clear documentation of either an mRNA or Sputnik V primary vaccine series. The unequal sample sizes and differing ratios of naïve/convalescent participants between groups reflect the availability of such complete datasets within the respective cohorts. No breakthrough infections were detected in any of the enrolled participants during the observation period.

Cell culture.

Vero-E6 cells expressing transmembrane protease serine 2 (TMPRSS2) (BPS Biosciences, cat. no. 78081) were maintained in Dulbecco's modified Eagle's medium (DMEM; Gibco, cat. no. 11965092) supplemented with 10 % heat-inactivated fetal bovine serum (FBS; Gibco, cat. no. A5256801), 1 % minimum essential medium with non-essential amino acids (Gibco, cat. no. 11140050), 100 U/mL penicillin and 100 μg/mL streptomycin (Gibco, cat. no. 15140122), 100 μg/mL normocin (InvivoGen, cat. no. ant-nr), and 3 μg/mL puromycin (InvivoGen, cat. no. ant-pr). Expi293F cells (Gibco, cat. no. A14527) were maintained in Expi293 Expression Medium (Gibco, cat. no. A1435102).

Recombinant protein production.

SARS-CoV-2 spike ectodomain proteins were produced using mammalian expression systems as previously described. A codon-optimized sequence encoding spike protein from the wild type ancestral strain (WT; ancestral Wuhan-Hu-1, GenBank: MN908947) was cloned into a pCAGGs expression vector. Recombinant protein was expressed in Expi293F cells using the ExpiFectamine 293 Transfection Kit (Thermo Fisher Scientific). Cell culture supernatants were harvested 72 h post-transfection, clarified by centrifugation at 4000 ×*g*, filtered, and purified using Ni^{2+}-nitrilotriacetic acid (Ni-NTA) agarose (Qiagen, cat. no. 30210). Purified proteins were concentrated using Amicon Ultracell centrifugal units (EMD Millipore, cat. no. C7715), buffer-exchanged to phosphate-buffered saline (1× PBS, pH 7.4), verified by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE), and stored at −80 °C until use.

Enzyme-linked immunosorbent assay (ELISA).

IgG binding antibody titers against SARS-CoV-2 WT spike proteins were measured using an in-house ELISA. Briefly, 96-well microtiter plates (Immulon 4 HBX; Thermo Scientific, cat. no. 439454) were coated overnight at 4 °C with 2 μg/mL recombinant spike protein. After washing with 1× PBS supplement with 0.1 % Tween 20 (PBS-T) and blocking with 3 % milk powder in PBS-T for 1 h at room temperature, heat-inactivated sera were added in 2-fold serial dilutions starting at 1:100. Following 2-h incubation and washing, anti-human IgG (Fab-specific) horseradish peroxidase (HRP)-conjugated secondary antibody (Sigma-Aldrich, cat. no. A0293) was added at a 1:3000 dilution. After 1-h incubation and washing, *o*-phenylenediamine dihydrochloride substrate (SIGMAFAST) was added for 10 min, and the reaction was stopped with 3 M HCl. Optical density was measured at 490 nm using a Synergy H1 microplate reader (BioTek), and area under the curve (AUC) values were calculated using Prism 10 (GraphPad).

Replication competent SARS-CoV-2 neutralization assay.

The SARS-CoV-2 isolate USA-WA.1/2020 was used as a wild-type/ancestral strain (BEI Resources; NR-52281), to measure neutralizing antibody titers using a multicycle microneutralization assay in a BSL-3 facility. Vero-E6 TMPRSS2 cells (2×10^4 cells/well) were seeded in 96-well plates 24 h prior to infection. Heat-inactivated sera were 3-fold serially diluted starting at 1:10 in modified Eagle's medium (1xMEM) and incubated with 10,000 x the 50 % tissue culture infectious dose ($TCID_{50}$) of virus for 1 h at room temperature. Virus-serum mixtures were transferred to cell plates and incubated for 1 h at 37 °C. After removing the inoculum, 1xMEM supplemented with 2 % FBS was added, and plates were incubated for 48 h at 37 °C. Cells were fixed with 10 % formaldehyde overnight at 4 °C, permeabilized with 0.1 % Triton X-100, and blocked with 3 % bovine serum albumin (BSA) in PBS. Biotinylated anti-SARS-CoV nucleoprotein mAb 1C7C7 (1 μg/mL) was added and incubated for 2 h, followed by HRP-conjugated streptavidin (1:2000) for 1 h. OPD substrate was added for 10 min, stopped with 3 M HCl, and optical density was measured at 490 nm. The 50 % inhibitory dilution (ID_{50}) was calculated using non-linear regression analysis with 100 % and 0 % constraints.

2.1. Statistical analysis

Mixed effects modeling was performed to assess vaccine platform effects on $\log_{10}$-transformed antibody titers, accounting for repeated measures within individuals using R (lme4 package). Models included fixed effects for vaccine type, exposure history, time, and their interactions, with random intercepts and slopes for participants. One participant with only one sera sample after second dose of vaccine was excluded from the model dataset. Post-hoc comparisons were conducted using estimated marginal means with Bonferroni correction. Statistical significance was set at $p < 0.05$.

3. Results

Study design and participants.

We selected participant samples from the VIVA Clinical Core to conduct a longitudinal immunogenicity study (pre-vaccination up to 200 days post-vaccination) comparing immune responses mounted by study participants receiving BNT162b2 or mRNA-1273 vaccines ($n = 28$; 14 naïve, 14 convalescent) or Sputnik V ($n = 44$; 34 naïve, 10 convalescent) as their primary COVID-19 immunization (Table 1). Participants were categorized by prior infection status based on pre-vaccination serology against SARS-CoV-2. Blood samples were collected at pre-vaccination (baseline), inter-dose (15 days post-vaccination), peak post-dose 2 (30 days post-vaccination), 120 days post-vaccination, and 180–200 days post-vaccination to evaluate the potency of binding and neutralizing antibodies.

Table 1
Characteristics of participants in Sputnik V and mRNA vaccines cohorts.

		Sputnik V		mRNA vaccines		Total (n = 72)
		Convalescent (n = 10)	Naïve (n = 34)	Convalescent (n = 14)	Naïve (n = 14)	
Age (median [min-max])		45 [22–60]	44 [26–73]	36 [26–47]	36 [26–47]	39 [22–73]
Sex	Female	8 (80 %)	19 (56 %)	9 (64 %)	10 (71 %)	46 (64 %)
	Male	2 (20 %)	15 (44 %)	5 (36 %)	4 (29 %)	26 (36 %)
Race	African American	0 (0 %)	0 (0 %)	2 (14 %)	0 (0 %)	2 (3 %)
	Asian	0 (0 %)	0 (0 %)	3 (21 %)	1 (7 %)	4 (6 %)
	Caucasian	10 (100 %)	34 (100 %)	8 (57 %)	11 (79 %)	63 (88 %)
	More than one race	0 (0 %)	0 (0 %)	1 (7 %)	1 (7 %)	2 (3 %)
	Other	0 (0 %)	0 (0 %)	0 (0 %)	1 (7 %)	1 (1 %)
Vaccine type	Sputnik V	10 (100 %)	34 (100 %)	0 (0 %)	0 (0 %)	44 (61 %)
	mRNA-1273	0 (0 %)	0 (0 %)	5 (36 %)	5 (36 %)	10 (14 %)
	BNT162b2	0 (0 %)	0 (0 %)	9 (64 %)	9 (64 %)	18 (25 %)
Days from infection to vaccine (median [min-max])		148 [2–265]	N/A	278 [19–341]	N/A	263 [2–341]

Platform-specific antibody responses.

mRNA vaccination resulted in substantially higher peak antibody responses compared to Sputnik V in participants with and without pre-existing immunity. In convalescent individuals, mRNA vaccines achieved 5.2-fold higher binding antibodies (GMT: 8704 vs 1674) and 3.4-fold higher neutralizing antibodies (GMT: 1022 vs 297) at peak post-dose 2 compared to Sputnik V recipients. This advantage was even more pronounced in naïve individuals, with 21.7-fold higher binding titers (GMT: 2753 vs 127) and 5.3-fold higher neutralizing activity (GMT: 103 vs 19) **(Fig. 1. A and B)**. Mixed effects modeling confirmed that these differences were statistically significant for binding antibodies in both naïve (log_{10} difference: 0.952, $p < 0.001$) and convalescent populations (log_{10} difference: 0.391, $p < 0.05$), as well as for neutralizing antibodies in naïve individuals (log_{10} difference: 0.483, $p < 0.001$) (Table 2).

Sustained antibody superiority with similar decay kinetics.

The most striking finding was the sustained superiority of mRNA-vaccine induced responses despite equivalent decay kinetics between platforms. Mixed effects modeling of post-peak antibody dynamics (14–180 days post-dose 2) revealed that both vaccine platforms showed similar decay rates, with interaction terms for vaccine platform × time not reaching statistical significance for either binding ($p = 0.35$) or neutralizing antibodies ($p = 0.10$). Both platforms demonstrated equivalent durability with similar half-lives of approximately 145 days for binding antibodies and 155 days for neutralizing antibodies **(Table 2)**.

At 120 days post-peak, mRNA-vaccinated participants with hybrid immunity maintained binding antibody levels 4.9-fold higher than Sputnik V recipients (GMT: 3979 vs 754). Neutralizing antibody durability showed similar patterns, with 1.8-fold higher levels persisting in the mRNA vaccinated group (GMT: 444 vs 252). In naïve individuals, the sustained advantage was even more pronounced, with both BNT162b2 and mRNA-1273 maintaining 16.1-fold higher binding and 4.4-fold higher neutralizing antibodies at 120 days **(Fig. 1 C)**. This sustained superiority results from higher initial peak responses that are maintained over time rather than differential decay rates between platforms.

Population-specific platform effects.

The vaccine platform advantage varied substantially by exposure history. In immunologically naïve individuals, mRNA vaccine superiority was most pronounced, with highly significant differences for both binding and neutralizing antibodies ($p < 0.001$). Convalescent populations showed significant differences for binding antibodies ($p = 0.036$), with neutralizing antibody responses differing at a similar magnitude without reaching statistical significance ($p < 0.001$) (Table 2). This population-dependent effect suggests that the mRNA platform advantage is particularly critical in individuals without prior SARS-CoV-2 exposure (**Fig. 1D**). This pronounced difference in naïve individuals implies that the mRNA platform may be especially beneficial for establishing a robust primary immune response.

4. Discussion

Our study provides the first direct longitudinal comparison of mRNA vaccines and adenoviral vector Sputnik V vaccine immunogenicity in cohorts of naïve and convalescent individuals. Three key findings emerge: (i) mRNA vaccines induce markedly superior peak antibody responses regardless of prior infection status, (ii) mRNA vaccines demonstrate superior sustained antibody levels through 6 months post-vaccination, and (iii) the platform advantage is most pronounced in immunologically naïve individuals where primary immune responses are critical.

These platform differences likely reflect fundamental mechanistic distinctions. mRNA vaccines deliver antigen continuously over several days through local translation [6], while adenoviral vectors may face limitations from pre-existing vector immunity and reduced antigen expression duration [7]. The heterologous Ad26/Ad5 strategy in Sputnik V was designed to overcome vector immunity [8], but our data suggest this approach remains less immunogenic than mRNA platforms. While Sputnik V vaccines elicit potent Fc effector functions comparable to mRNA platforms, these enhanced activities do likely not compensate for the markedly inferior neutralizing antibody magnitude and durability we observed [9].

The differential impact of prior infection is particularly noteworthy. While mRNA platforms synergize effectively with pre-existing immunity through enhanced germinal center formation and memory B cell development [10,11], the platform advantage was consistent in both naïve and convalescent populations. mRNA vaccines maintained statistically significant superiority for both binding and neutralizing antibodies in both populations, indicating that platform choice matters even in populations with pre-existing immunity. The strong effect in naïve participants suggests that mRNA vaccines may confer greater protection in populations with limited baseline immunity. Nevertheless, it should be noted that T cell responses, which were not assessed here, can play a critical role in protection, particularly in individuals with attenuated antibody responses [12]. Future comparative studies evaluating cellular immunity across vaccine platforms in immunocompromised cohorts will be essential to fully define these platform-specific advantages.

The sustained higher antibody levels demonstrated by mRNA vaccines, with equivalent decay rates for both binding and neutralizing antibodies, have important clinical implications. Given that neutralizing antibody levels are highly predictive of immune protection from symptomatic SARS-CoV-2 infection [2], the sustained higher levels observed with mRNA vaccination may translate to longer duration of protection, though cross-reactivity against emerging variants remains to be evaluated.

The similar antibody decay kinetics observed between mRNA and Sputnik V vaccines contrast with reports from other adenoviral platforms. Studies of ChAdOx1 nCoV-19 and Ad26.COV2·S have described slower waning relative to mRNA vaccines in some cohorts [13–15],

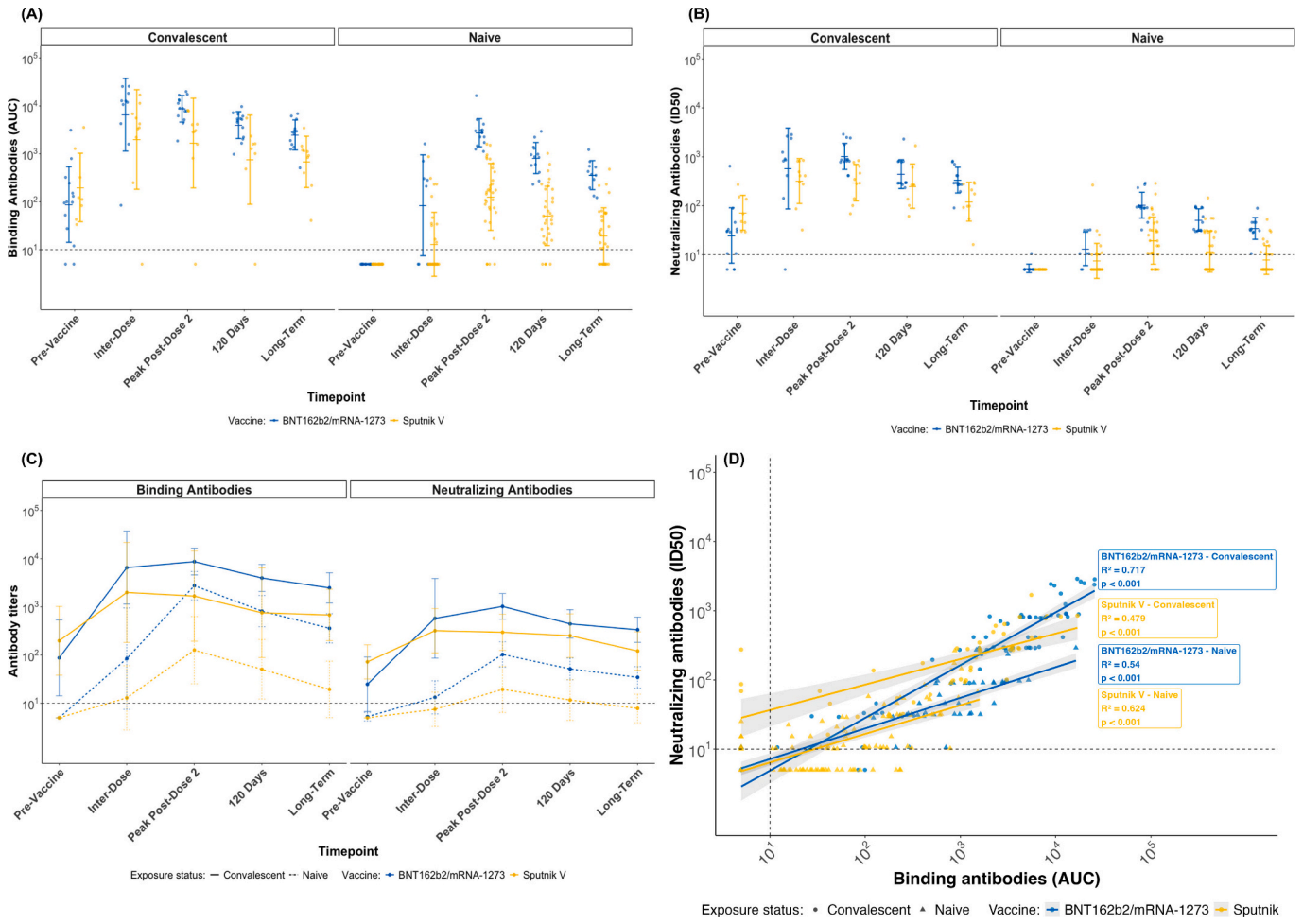

Fig. 1. Comparative analysis of humoral immune responses to Sputnik V and mRNA vaccines over time. (A) Binding antibody responses following BNT162b2 or mRNA-1273 and Sputnik V vaccination in convalescent and naïve participants. Binding antibody levels (AUC) measured by ELISA at five timepoints: pre-vaccine, inter-dose, peak post-dose 2, 120 days post-vaccination, and long-term follow-up (180–200 days). Data shown separately for convalescent (left panel) and naïve (right panel) participants. Blue circles represent BNT162b2 or mRNA-1273 recipients, yellow circles represent Sputnik V recipients. Individual data points are shown with geometric mean and 95 % confidence intervals. The dashed horizontal line indicates the assay detection limit (AUC = 10). **(B)** Neutralizing antibody responses following BNT162b2 or mRNA-1273 and Sputnik V vaccination in convalescent and naïve participants. Neutralizing antibody levels (ID_{50}) measured at five timepoints: pre-vaccine, inter-dose, peak post-dose 2, 120 days post-vaccination, and long-term follow-up (180–200 days). Data shown separately for convalescent (left panel) and naïve (right panel) participants. Blue circles represent BNT162b2 or mRNA-1273 recipients, yellow circles represent Sputnik V recipients. Individual data points are shown with geometric mean and 95 % confidence intervals. The dashed horizontal line indicates the assay detection limit (ID_{50} = 10). **(C)** Geometric mean binding and neutralizing antibody responses over time by vaccine type and exposure status. Geometric mean binding antibodies (left panel) and neutralizing antibodies (right panel) with 95 % confidence intervals across vaccination timepoints. Solid lines represent convalescent participants, dashed lines represent naïve participants. Blue lines show BNT162b2 or mRNA-1273 vaccines responses, yellow lines show Sputnik V responses. Horizontal dashed line indicates assay detection limit. **(D)** Correlation between binding and neutralizing antibodies across vaccination timepoints. Scatter plot showing relationship between binding antibodies (AUC, x-axis) and neutralizing antibodies (ID_{50}, y-axis) for all participants and timepoints. Circles represent convalescent participants; triangles represent naïve participants. Blue symbols and regression line show BNT162b2 or mRNA-1273 data, yellow symbols and regression line show Sputnik V data. Vertical dashed line indicates binding antibody detection limit (AUC = 10), horizontal dashed line indicates neutralizing antibody detection limit (ID_{50} = 10). R^2 values and *p*-values for correlations are shown in the legend box. Grey shading represents 95 % confidence intervals for regression lines. Trend lines with 95 % confidence intervals demonstrate positive correlations for all groups, with R^2 values ranging from 0.479 to 0.717 (all $p < 0.001$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

whereas others reported comparable or faster decay [16,17]. These discrepancies likely reflect differences in vector backbone, dosing regimen, antigen design, or cohort composition. Notably, Sputnik V employs a heterologous Ad26/Ad5 strategy, distinct from the homologous or single-dose designs of other adenoviral vaccines [9,18]. The comparable decay rates between Sputnik V and mRNA vaccines, despite differing peak responses, suggest that platform-specific differences primarily influence the magnitude of the initial antibody response rather than its persistence.

Several limitations should be acknowledged. First, the mRNA vaccine cohort was recruited in New York City, USA while the Sputnik V cohort was from Argentina, introducing potential confounding factors related to genetic background, environmental exposures, and healthcare systems. Additionally, the vaccination periods differed temporally between cohorts, which may have influenced baseline immune status and circulating viral variants. These geographical and temporal differences may partially account for observed immunogenicity differences beyond intrinsic vaccine platform properties. Second, our study did not assess the breadth of cross-reactive responses beyond the ancestral strain. This remains an important consideration, as multiple reports have shown that neutralizing antibody titers elicited by vaccines based on the ancestral SARS-CoV-2 strain decline substantially against emerging variants [19,20], underscoring the need for periodic updates to vaccine strain composition. Third, the Sputnik V cohort was, on average, older

Table 2
Mixed effects modeling results for post-peak antibody decay analysis.

Parameter	Binding Antibodies	Neutralizing Antibodies
Model Characteristics		
Participants (n)	71	71
Observations (n)	207	207
Main Effects		
BNT162b2/mRNA1273 (Naïve, Reference)	3.54 ± 0.16***	2.07 ± 0.10***
Sputnik V vs BNT162b2/mRNA1273	−1.34 ± 0.18***	−0.74 ± 0.11***
Convalescent vs Naïve	0.44 ± 0.21*	0.97 ± 0.13***
Decay rate (log_{10}/day)	−0.0054 ± 0.0007***	−0.0030 ± 0.0004***
Interaction Effects		
Sputnik V × Time	0.0007 ± 0.0007	0.0007 ± 0.0004†
Convalescent × Time	0.0022 ± 0.0007**	−0.0000 ± 0.0004
Sputnik V × Convalescent	0.57 ± 0.27*	0.24 ± 0.17
Decay Kinetics		
Naïve (reference) group half-life (days)	−55.4	−99.8
Half-life 95 % CI	(44.9–72.5)	(79.2–134.9)

The above table summarize mixed-effects modeling results for binding and neutralizing antibody responses in convalescent and naïve individuals and the overall mRNA vaccines - Sputnik V longitudinal cohort. p-values: *$p < 0.05$, ***$p < 0.001$. Estimates represent log_{10} differences (mRNA vaccines - Sputnik V). Significance: ***$p < 0.001$, **$p < 0.01$, $p < 0.05$, †$p < 0.1$. The non-significant Sputnik V × Time interactions indicate similar decay rates between vaccine platforms.

than the mRNA cohort (median age 44–45 vs. 36). As advanced age is a well-known factor associated with reduced vaccine immunogenicity, this difference represents a significant potential confounder and may have contributed to the lower antibody responses observed in the Sputnik V group. Fourth, within the convalescent groups, the median time from infection to first vaccination dose was substantially different (148 days for Sputnik V vs. 278 days for mRNA). This variability in the interval between natural infection and vaccination introduces another potential confounder, as the maturity of the pre-existing memory response can influence post-vaccine titers.

In conclusion, mRNA vaccines demonstrate superior immunogenicity and sustained antibody levels compared to Sputnik V, with particularly pronounced advantages in infection-naïve individuals and sustained higher levels in convalescent recipients. These differences support prioritizing mRNA vaccines when available and suggest that Sputnik V recipients, especially those without prior infection, may benefit from earlier booster vaccination.

5. Conclusions

This comparative analysis demonstrates that mRNA vaccination provides markedly superior antibody responses and sustained higher titers compared to adenoviral vector platforms. The advantage in sustained antibody titers has important implications for protection duration and booster strategies. These findings support prioritizing mRNA vaccines where durable humoral immunity is critical. Optimal boosting strategies for adenoviral vector vaccines remain to be determined and should be guided by platform-specific studies that consider cellular immunity and variant-specific protection.

CRediT authorship contribution statement

Anass Abbad: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Brian Lerman:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Jordan Ehrenhaus:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Diego Sebastian Ojeda:** Writing – review & editing, Resources, Conceptualization. **Charles Gleason:** Writing – review & editing, Resources, Formal analysis, Data curation, Conceptualization. **Gagandeep Singh:** Writing – review & editing, Resources. **Zain Khalil:** Writing – review & editing, Data curation. **Ana Silvia Gonzalez-Reiche:** Writing – review & editing, Data curation. **Komal Srivastava:** Writing – review & editing, Data curation. **Ana Fernandez Sesma:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Andrea Gamarnik:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Viviana Simon:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Florian Krammer:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The Icahn School of Medicine at Mount Sinai has filed patent applications relating to SARS-CoV-2 serological assays, NDV-based SARS-CoV-2 vaccines influenza virus vaccines, and influenza virus therapeutics which list FK as co-inventor and FK has received royalty payments from some of these patents. Mount Sinai has spun out a company, Castlevax, to develop SARS-CoV-2 vaccines. FK is a co-founder and scientific advisory board member of Castlevax. FK has consulted for Merck, GSK, Sanofi, Curevac, Gritstone, Seqirus, and Pfizer and is currently consulting for 3rd Rock Ventures and Avimex. The Krammer laboratory is also collaborating with Dynavax on influenza vaccine development.

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Data availability

Data will be made available on request and will also become available in ImmPort (ImmPort# SDY1909).

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