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Fig. S1. Detection of AIM⁺ **T cells. (A)** Representative flow cytometric gating strategy showing the identification of AIM⁺ memory CD4⁺ and CD8⁺ T cells via flow cytometry. (**B**) Stimulation indices of individual donor responses at 6–9M. (**C**) Frequencies of intracellular AIM⁺ memory CD4⁺ T cells after DMSO and peptide pool stimulation. (**D**) Frequencies of AIM⁺ memory CD4⁺ T cells measured by intracellular staining, plotted with raw values (left) and DMSO background subtracted values (right). Statistical significance was determined by Mann–Whitney U test (C and D). **P* < 0.05, ***P* < 0.01, ****P* < 0.001, *****P* < 0.0001. Bars shown median.



Fig. S2. Effect of vaccination on the frequency of spike-specific T cells. (**A**) Frequencies of AIM⁺ memory CD4⁺ T cells targeting different regions of SARS-CoV-2. (**B**) Frequencies of AIM⁺ memory CD8⁺ T cells targeting the spike protein of SARS-CoV-2. Statistical significance was determined by Mann–Whitney U test (A and B). n.s. = P > 0.05, *P < 0.05, *P < 0.01, ****P < 0.001, ****P < 0.001. Bars shown median.



Fig. S3. Characterization of T cell cytokine production and inhibitory receptor expression. (A) Permutation test comparisons of cytokine expression profiles among AIM⁺ memory CD4⁺ T cells (related to Fig. 2C). (B) Percentages of IFN- γ^+ spike-specific memory CD8⁺ T cells with polyfunctional cytokine and cytotoxic molecule expression after peptide stimulation. (C) Representative flow cytometry plots showing the identification of inhibitory receptor expression among tetramer-binding CD8⁺ T cells. (D) Percentages of tetramer-binding CD8⁺ T cells with inhibitory receptor expression. Statistical significance was determined by permutation test (A) and Mann–Whitney U test (B and D). n.s. = P > 0.05, *P < 0.05, **P < 0.01, ****P < 0.001. Bars shown median.



Fig. S4. Classification of AIM⁺ **populations sorted for scRNA-seq.** (**A**) Representative flow cytometric gating strategy for the identification and sorting of AIM⁺ CD4⁺ and CD8⁺ T cells for scRNA-seq. (**B**) Distribution of conventional AIM⁺ cells with CD4 or CD8 protein expression separated by donor and time point. Cells classified as 'other' either lacked expression of CD4 and CD8 or expressed both CD4 and CD8. (**C**) UMAP and clustering of all sorted cells, including NK cells and unconventional T cells. (**D**) Classification of NK cells and unconventional T cells. (**E**) Expression of transcripts corresponding to conventional and unconventional T cell subsets. (**F**) Distribution of donor groups and time points across each UMAP cluster. (**G**) Frequencies of sorted AIM⁺ memory CD4⁺ and CD8⁺ T cells after spike peptide pool stimulation. (**H**) Comparison of frequencies of AIM⁺ populations after DMSO and spike peptide pool stimulation.



Fig. S5. Protein expression among spike-specific T cells determined via CITE-seq. (A) Heatmap showing protein expression measured via CITE-seq using a reduced panel for convalescent donors sampled on day 35. (**B**) Violin plots showing the expression of activation markers separated by donor group and time point.



Fig. S6. Transcriptomic comparison of spike-specific T cells before and after vaccination. (A) Proportions of AIM⁺ CD4⁺ T cells from individual donors belonging to each CD4⁺ T cell cluster. (B) GSEA summary of differentially expressed genes between CD4⁺ T cells at 6-9M versus 18M. (C) Dot plots of the percentages of CD4⁺ T cells from mild, severe and recently vaccinated donors with expression of *IFNG*. (D) Dot plots of the percentages of CD4⁺ T cells from mild, severe and recently vaccinated donors with expression of *IL10*. (E) Percentages of CD4⁺ T cells with expression of *IL10*. (F) Proportions of AIM⁺ CD8⁺ T cells from individual donors belonging to each CD8⁺ T cell cluster. Statistical significance was determined by Broad GSEA test (B) and Mann–Whitney U test (C and D). Adjusted p-values calculated using the Benjamini–Hochberg (B) method. n.s. = P > 0.05, *P < 0.05, **P < 0.01, ***P < 0.001



Fig. S7. Clonal characterization of spike-specific T cells before and after vaccination. (**A**) Proportions of CD4⁺ and CD8⁺ T cells classified by the degree of clonal expansion. (**B**) *IFNG* expression among expanded CD8⁺ T cell clonotypes after vaccination separated by donor.



Fig. S8. Transcriptomic signatures of CD8⁺ T cell clonotypes detected at one or both time points. (A) Volcano plot showing differentially expressed genes between existing and newly detected CD8⁺ T cell clonotypes at 18M. (B) GSEA summary of differentially expressed genes between existing and newly detected CD8⁺ T cell clonotypes at 18M. (C) GSEA plot showing significantly enriched pathways at 18M. WP: WikiPathways; R: Reactome. Statistical significance was determined by Mann–Whitney U test (A) and Broad GSEA test (C) and. Adjusted p-values calculated using the Bonferroni method (A). n.s. = P > 0.05, *P < 0.05



Fig. S9. Characterization of hybrid spike-specific T cell responses in donors with CLL. (A) Overview of donors and sampling time points from a cohort of patients undergoing treatment for CLL. (B) Frequencies of AIM⁺ memory CD4⁺ T cells. (C) Frequencies of AIM⁺ memory CD8⁺ T cells. (D) Percentages of AIM⁺ memory CD4⁺ T cells expressing cytokines. (E) Percentages of total memory CD8⁺ T cells expressing IFN- γ . Statistical significance was determined by paired Wilcoxon Signed-Rank Test (B, C, D, E). n.s. = P > 0.05, *P < 0.05



Fig. S10. Summary of hybrid T cell immunity shaped by infection and vaccination. Schematic representation of the key findings.

Donor group and time point	Characteristic	Value
Mild (non-hospitalized)	Total number	50
	Number with paired time points	31
6–9 months convalescence	Total number	44
• • • • • • • • • • • • • • • • • • • •	Unvaccinated	44
	Median age at infection (range)	54.5 (43-78)
	Male / Female	33 / 11 (75/25
		%)
18 months convalescence	Total number	37
	Unvaccinated	3
	Vaccinated	34
	Vaccine platform	
	(Comirnaty, SpikeVax, Vaxzevria,	27, 3, 2, 2
	unknown)	/
	Median age at infection (range)	57 (43-78)
	Male / Female	28 / 9 (76/24
		%)
Severe (hospitalized)	Total number	53
	Number with paired time points	24
6–9 months convalescence *	I otal number	45
	Unvaccinated	45
	Median age at infection (range)	57 (33-68)
	Male / Female *	34 / / (76/16
		%)
	Admitted to ICU	26
		21
18 months convalescence		32
	Unvaccinated	1
		25
		10 0 0 0
		10, 0, 0, 3
	Modian ago at infaction (rango)	57 5 (22-76)
	Mala / Fomala	37.3(33-70)
		23/9(12/20
	Admitted to ICU	/0)
	Required ventilator	10
		10

Table S1. Summary of donors with a history of mild or severe disease.

The exact date of infection or vaccination was unavailable for four donors with mild disease and two donors with severe disease. *Clinical information was unavailable from four donors. ICU: intensive care unit.

Donor group and time point	Characteristic	Value
Mild (non-hospitalized)	Total number	14
 Paired 6–9M and 18M 	Median age at infection (range)	54 (43-66)
time points for each	Male / Female	10 / 4
donor	HLA combinations	
 All donors vaccinated 	A24	3
at the 18M time point	A2 A24	6
	A2 B7	2
	A24 B7	2
	A2 A24 B7	1
Severe (hospitalized)	Total number	14
 Paired 6–9M and 18M 	Median age at infection (range)	57.5 (33-68)
time points for each	Male / Female	11 / 3
donor	HLA combinations	
 All donors vaccinated 	A2	5
at the 18M time point	A24	5
- 1	A2 A24	2
	A2 B7	1
	A2 A24 B7	1

 Table S2. Summary of donors selected for tetramer analysis.

Table S3. Summary of donors selected for single-cell RNA-sequencing (scRNA-seq).

Donor group and time point	Characteristic	Value
Mild	Donor IDs	22, 123, 126
 Non-hospitalized 	Age	67, 59, 57
 6–9 months convalescence 	Sex	M, M, M
 18 months convalescence 	Vaccine platform	
	Vaxzevria (Donor IDs)	22
	Comirnaty (Donor IDs)	123, 126
Severe	Donor IDs	53, 73, 145
 Non-hospitalized 	Age	56, 62, 56
 6–9 months convalescence 	Sex	M, F, F
 18 months convalescence 	Vaccine platform	
	Comirnaty (Donor IDs)	53, 73
	Unknown (Donor IDs)	145
Recently vaccinated	Donor IDs	4868
 Non-hospitalized 	Age	54
 Baseline: 2 weeks before vaccination 	Sex	F
or 13 months convalescence	Vaccine platform	
 Dose 2+: 2 weeks after second dose 	SpikeVax (Donor IDs)	4868
vaccination or 15 months		
convalescence		
Recently convalescent	Donor IDs	850, 852, 854
 Non-hospitalized 	Unvaccinated	3
 Day 35 convalescence 	Age	Unavailable
 Unvaccinated 	Sex	F, F, M

Donor group and time point	Characteristic	Value
B cell abnormality	Total number	7
 Treated with BTK inhibition 	Median age at convalescent time point	69
for CLL	(range)	(46-77)
 Convalescent 	Male / Female	4/3
Post-dose 4	Hospitalized	6

Table S4. Summary of donors with B cell abnormalities (CLL).

CLL: chronic lymphocytic leukemia; BTK: Bruton's tyrosine kinase

Table S5. Summary of healthy vaccinated donors.

Donor group and time point	Characteristic	Value
 Vaccinated healthy controls 3 month post-vaccination follow-up (two doses received) 18 month post-vaccination follow-up (three or four doses received) 	Total number	14
With breakthrough infection	Total number	5
	Median age at vaccination	32
	(range)	(26-55)
	Male / Female	2/3
	Vaccine platform	
	Comirnaty only	2
	Comirnaty and SpikeVax	3
	Clinical history	
	Two doses > breakthrough	1
	Two doses > breakthrough > third dose	1
	Three doses > breakthrough	3
Without breakthrough infection	Total number	9
 All received four vaccine 	Median age at vaccination	46
doses by the 18 month	(range)	(28-59)
follow-up	Male / Female	4 / 5
	Vaccine platform	
	Comirnaty only	6
	Comirnaty and SpikeVax	3

STEP 1: Stain for viability at room temperature for 10 minutes.							
Marker	Fluorophore	Supplier	Dilution	Product number	Clone		
LIVE/DEAD	For 405 nm	Invitrogen	1X in PBS	L34957	-		
Fixable Aqua	excitation						
STEP 2: Stain for c	hemokine recep	otors at 37°C fo	or 10 minutes.		1		
Marker	Fluorophore	Supplier	Dilution	Product	Clone		
				number			
CCR7	APC-Cy7	BioLegend	1:50	353212	G043H7		
CCR4	BB700	BD	1:50	566475	1G1		
CCR6	BUV737	BD	1:75	612780	11A9		
CXCR3 AF647		BioLegend	1:100	353712	G025H7		
STEP 3: Stain with	remaining antib	odies at room	temperature for	or 30 minutes i	n BD Brilliant		
Stain Buffer Plus.							
Marker	Fluorophore	Supplier	Dilution	Product	Clone		
				number			
CD40L	BV421	BioLegend	1:25	310824	24-31		
4-1BB	PE-Cy7	BioLegend	1:25	309818	4B4-1		
CD4	BUV496	BD	1:25	612936	SK3		
CD14	BV510	BioLegend	1:100	301842	M5E2		
CD19	BV510	BioLegend	1:100	302242	HIB19		
CD45RA	BV570	BioLegend	1:200	304132	HI100		
CD69	BV650	BioLegend	1:50	310934	FN50		
CD3	BUV805	BD	1:50	612895	UCHT1		
CD8	BUV395	BD	1:250	563795	RPA-T8		
STEP 4: Wash and fix cells in 1% paraformaldehyde.							

Table S6. Surface staining protocol for flow cytometry.

STEP 1: Stain for chemokine receptors at 37°C for 10 minutes.								
Marker	Fluorophore	Supplier	Dilution	Product number	Clone			
CCR7	APC-Cy7	BioLegend	1:50	353212	G043H7			
CCR4	BB700	BD	1:50	566475	1G1			
CCR6	BUV737	BD	1:75	612780	11A9			
CXCR3	AF647	BioLegend	1:50	353712	G025H7			
STEP 2: Stain wit in BD Brilliant Sta	h surface antibod in Buffer Plus.	ies and viabil	ity dye at ro	om temperatur	e for 30 minutes			
Marker	Fluorophore	Supplier	Dilution	Product number	Clone			
PD-1	BV711	BioLegend	1:25	329928	EH12.2H7			
CD4	BUV496	BD	1:25	612936	SK3			
CD14	BV510	BioLegend	1:100	301842	M5E2			
CD19	BV510	BioLegend	1:100	302242	HIB19			
CD45RA	BV570	BioLegend	1:200	304132	HI100			
CD8	BUV395	BD	1:250	563795	RPA-T8			
LIVE/DEAD	For 405 nm	Invitrogen	1:1667	L34957	-			
Fixable Aqua	excitation							
CD38	APC-R700	BD	1:50	564979	HIT2			
STEP 3: Fix and (Invitrogen, #00-5	permeabilize with 523-00) according	FoxP3 Trans g to the provi	cription Fac ded protoco	tor Staining Βι Ι.	Iffer Set			
STEP 4: Stain wit Brilliant Stain Buf	h intracellular ant fer Plus and 1X P	ibodies at roc ermeabilizatio	om temperat on Buffer.	ure for 30 minu	utes in BD			
Marker	Fluorophore	Supplier	Dilution	Product number	Clone			
CD40L	BV421	BioLegend	1:25	310824	24-31			
IL-17A	eFluor660	Invitrogen 1:25 50		50-7178-42	eBio64CAP17			
IL-2	PE-Dazzle594	BioLegend	1:33	500344	MQ1-17H12			
4-1BB	PE-Cy7	BioLegend	1:100	309818	4B4-1			
TNFa	BV650	BD	1:166	563418	MAb11			
CD3	BUV805	BD	1:250	612895	UCHT1			
CD69	BUV563	BD	1:200	748764	FN50			
IFN-γ	PE	BioLegend	1:400	506507	B27			
Granzyme B	BB790	BD	1:500	624296	GB11			
STEP 5: Wash and fix cells in 1% paraformaldehyde.								

Table S7. Surface and intracellular staining protocol for flow cytometry.

Table	S8.	Tetramer.	surface	and	intrace	ellular	staining	protocol	for flow	cytometry	-
		,						p			-

Reagent Fluorophore Supplier Final conc. Product number Clone Dasatinib - STEMCELL 50 µM 73082 - STEP 2: Incubate with one relevant PE tetramer/tetramer pool at room temperature for 20 minutes. Each tetramer should be equivalent to 0.2 µl of pMHC (0.5 µg/ml, total 10µl volume). Reagent Fluorophore Tetramer pool consisting of: SARS-CoV-2 ORF3 A*0201 LLXDRLNQL Fluorophore PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE CMV pp65 A*0201 NLVPMVATV PE SARS-CoV-2 ORF3 A*0201 NLVPMVATV PE CMV pp65 A*0201 NLVPMVATV PE SARS-CoV-2 spike A*0201 YLOPRTFLL BV421 SARS-CoV-2 spike A*0201 YLOPRTFLL BV421 SARS-CoV-2 spike A*0201 YLOPRTFLL BV421 SARS-CoV-2 spike A*0201 YLOPRTFLL BV421 SARS-CoV-2 spike A*0202 SPRRARSVA BV421 SARS-CoV-2 spike A*0202 SPRRARSVA BV421 SARS-CoV-2 spike A*0203 SPRRARSVA BV421 SARS-CoV-2 spike A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Fluorophore Supplier Dilution
Image: Constant in the
Dasatinib - STEMCELL 50 µM 73082 - STEP 2: Incubate with one relevant PE tetramer/tetramer pool at room temperature for 20 minutes. Each tetramer should be equivalent to 0.2 µl of pMHC (0.5 µg/ml, total 10µl volume). Reagent Fluorophore Tetramer pool consisting of: SARS-CoV-2 nucleocapsid A*0201 LLUDRLNQL PE SARS-CoV-2 ORF3A A*0201 ALSKGVHFV PE PE SARS-CoV-2 ORF3A A*0201 LLYDANYFL PE CMV pp65 A*0201 NLVPMVATV PE SARS-CoV-2 nucleocapsid B*0702 SPRWYFYYL PE PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 SARS-CoV-2 spike A*0201 mLivitrogen 11x in L34957 - STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Fuorophore S3212 G043H7 CXCR7 APC-Cy7 BioLegend
STEP 2: Incubate with one relevant PE tetramer/tetramer pool at room temperature for 20 minutes. Each tetramer should be equivalent to 0.2 µl of pMHC (0.5 µg/ml, total 10µl volume). Reagent Fluorophore Tetramer pool consisting of: SARS-CoV-2 nucleocapsid A*0201 LLDRLNQL SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*2020 QYIKWPWYI BV421 SARS-CoV-2 spike A*2020 QYIKWPWYI BV421 SARS-CoV-2 spike A*2020 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Fluorophore Supplier Dilution Product number Clone
minutes. Each tetramer should be equivalent to 0.2 µl of pMHC (0.5 µg/ml, total 10µl volume). Reagent Fluorophore Tetramer pool consisting of: SARS-CoV-2 nucleocapsid A*0201 LLLDRLNQL PE SARS-CoV-2 ORF3A A*0201 ALSKGVHFV PE SARS-CoV-2 ORF3A A*0201 LLYDANYFL SARS-CoV-2 ORF3A A*0201 LLYDANYFL PE CMV pp65 B*0702 TPRVTGGGAM PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*020 QYIKWPWYI BV421 SARS-CoV-2 spike A*0201 NLVPMVATV BV421 SARS-CoV-2 spike A*0702 SPRRARSVA BV421 SARS-CoV-2 spike A*0702 SPRRARSVA BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Fluorophore Supplier Dilution Product number Clone LIVE/DEAD For 405 nm Invitrogen 1X in L34957 - Fixable excitation Argua - - - Argua Invitrogen
Reagent Fluorophore Tetramer pool consisting of: SARS-CoV-2 nucleocapsid A*0201 LLLDRLNQL SARS-CoV-2 ORF3 A*0201 ALSKGVHFV PE SARS-CoV-2 ORF3 A*0201 ALSKGVHFV PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE CMV pp65 B*0702 TPRVTGGGAM PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent Reagent Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*2402 QYIKWPWYI BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Clone LIVE/DEAD For 405 nm Invitrogen 1X in L34957 - Fixable excitation PBS - - - Aqua Invitrogen 1X in L34957 - - GCR7 APC-Cy7 BioLegend 1:50 353212 G043H7 C
Tetramer pool consisting of: PE SARS-CoV-2 nucleocapsid A*0201 LLIDRLNQL PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE CMV pp65 B*0702 TPRVTGGGAM PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 NLVPMVATV BV421 SARS-CoV-2 spike A*0201 NLVPMVATV BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Marker Fluorophore Supplier Dilution Product number Clone LIVE/DEAD For 405 nm Invitrogen 1X in Fixable excitation PBS G043H7 Aqua Dilution Product number Clone CCR7 APC-Cy7 BioLegend 1:50 353212
SARS-CoV-2 ORF3a A*0201 ALSKGVHFV PE SARS-CoV-2 ORF3 A*0201 ALSKGVHFV PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE CMV pp65 B*0702 TPRVTGGGAM PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0202 YIKWPWYI BV421 SARS-CoV-2 spike A*0202 VIKWPWYI BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 SARS-CoV-2 spike A*0201 NLVPMVATV BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Marker Fluorophore Supplier Dilution Product number Clone CX7 APC-Cy7 BioLegend 1:500 353212 G043H7 CXCR3 PE-Cy5 BioLegend 1:100 75690 2A9-1 STEP 6: Stain with surface antibodies at room temperature for
SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE CMV pp65 B*0702 TPRVTGGGAM PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent Reagent Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0201 SPRARSVA BV421 SARS-CoV-2 spike A*0201 NLVPMVATV BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 SARS-CoV-2 spike B*0702 SPRPRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Marker Fluorophore Supplier Dilution Product number Clone CXCR3 PE-Cy5 BioLegend 1:50 353756 G025H7 CX3CR1 BUV615 BioLegend 1:200 563795 RPA-T8
SARS-CoV-2 ORF3 A*0201 LLYDANYFL PE SARS-CoV-2 nucleocapsid B*0702 SPRWYFYL PE CMV pp65 B*0702 TPRVTGGGAM PE CMV pp55 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*0202 SPRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. To minutes. Marker Fluorophore Supplier IVE/DEAD For 405 nm Invitrogen 1X in Fixable excitation PBS - Aqua Invitrogen 1200 353212 G043H7 CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CX3CR1 BUV615 BioLegend 1:200 563795 RPA-T8 CD38 BUV396 BioLegend 1:200 612946
SARS-CoV-2 nucleocapsid B'07/02 SPRWYFYYL PE CMV pp65 B*0702 TPRVTGGGAM PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent Reagent Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*2402 QYIKWPWYI BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Marker Fluorophore Supplier Dilution Product number Clone LIVE/DEAD For 405 nm Invitrogen 1X in L34957 - Fixable excitation PBS G043H7 - Aqua Invitrogen 1X in L34957 - CCR7 APC-Cy7 BioLegend 1:50 353212 G043H7 CXCR3 PE-Cy5 BioLegend 1:100 </td
CMV pp65 B*0702 1PKV1GGGAM PE CMV pp65 A*0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 SARS-CoV-2 spike A*2402 QYIKWPWYI BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Marker Fluorophore Supplier Dilution Product number Clone LIVE/DEAD For 405 nm Invitrogen 1X in STEP 5: Stain for chemokine receptors at 37°C for 10 minutes. Marker Fluorophore Marker Fluorophore Supplier Dilution Product number CCR7 APC-Cy7 BioLegend 1:50 353212 G043H7 CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CX3CR1 BUV615 BioLegend 1:200
CMV pp65 A '0201 NLVPMVATV PE STEP 3: Incubate with one relevant BV421 tetramer at room temperature for 20 minutes. Reagent Fluorophore SARS-CoV-2 spike A*0201 YLQPRTFLL BV421 BV421 SARS-CoV-2 spike A*2402 QYIKWPWYI BV421 SARS-CoV-2 spike B*0702 SPRRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. BV421 Marker Fluorophore Supplier Dilution Product number Clone LIVE/DEAD For 405 nm Invitrogen 1X in L34957 - Fixable excitation Invitrogen 1X in B4957 - Aqua Invitrogen 1X in B4957 - - STEP 5: Stain for chemokine receptors at 37°C for 10 minutes. Marker Fluorophore Supplier Dilution Product number Clone CXCR3 PE-Cy7 BioLegend 1:200 353212 G043H7 CXCR3 PE-Cy7 BioLegend 1:200 2A9-1 STEP 6: Stain with surface antibodi
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SARS-COV-2 spike A 0201 rtuber RTFLL B 421 SARS-COV-2 spike A*2402 QYIKWPWYI BV421 SARS-CoV-2 spike B*0702 SPRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. BV421 Marker Fluorophore Supplier Dilution Product number Clone LIVE/DEAD For 405 nm Invitrogen 1X in L34957 - Aqua excitation Invitrogen 1X in L34957 - Marker Fluorophore Supplier Dilution Product number Clone CCR7 APC-Cy7 BioLegend 1:50 353212 G043H7 CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CXCR3 PE-Cy5 BioLegend 1:200 563795 RPA-T8 DB Termerature Fluorophore Supplier Dilution Product number Clone <
SARS-COV-2 spike A 2402 QTRWPWT1 BV421 SARS-COV-2 spike B*0702 SPRARSVA BV421 CMV pp65 A*0201 NLVPMVATV BV421 STEP 4: Wash cells. Stain for viability at room temperature for 10 minutes. Marker Marker Fluorophore Supplier Dilution Product number Clone LIVE/DEAD For 405 nm Invitrogen 1X in L34957 - Aqua PBS - - - - Marker Fluorophore Supplier Dilution Product number Clone CCR7 APC-Cy7 BioLegend 1:50 353212 G043H7 CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CXCR3 PE-Cy5 BioLegend 1:100 750690 2A9-1 STEP 6: Stain with surface antibodies at room temperature for 30 minutes in BD Brilliant Stain Buffer Plus. Buffer Plus. Marker Fluorophore Supplier Dilution Product number Clone CD8 BUV396 BD 1:200 563795 RPA-T8 CD38 BUV396 BD
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MarkerFluorophoreSupplierDilutionProduct numberCloneCCR7APC-Cy7BioLegend1:50353212G043H7CXCR3PE-Cy5BioLegend1:200353756G025H7CX3CR1BUV615BioLegend1:1007506902A9-1STEP 6: Stain with surface antibodies at room temperature for 30 minutes in BD Brilliant Stain Buffer Plus.SupplierDilutionProduct numberCloneCD8BUV396BioLegend1:200563795RPA-T8CD38BUV496BD1:200612946HIT2LAG3BUV661BD1:200624285T47-530PD-1BUV737BD1:50612791EH12.1CD3BUV805BD1:50612895UCHT1CD14BV510BioLegend1:100301842M5E2CD19BV510BioLegend1:100302242HIB19
CCR7 APC-Cy7 BioLegend 1:50 353212 G043H7 CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CX3CR1 BUV615 BioLegend 1:100 750690 2A9-1 STEP 6: Stain with surface antibodies at room temperature for 30 minutes in BD Brilliant Stain Buffer Plus. Marker Fluorophore Supplier Dilution Product number Clone CD8 BUV396 BioLegend 1:200 563795 RPA-T8 CD38 BUV496 BD 1:200 612946 HIT2 LAG3 BUV661 BD 1:200 612945 T47-530 PD-1 BUV737 BD 1:50 612791 EH12.1 CD3 BUV805 BD 1:50 612895 UCHT1 CD14 BV510 BioLegend 1:100 301842 M5E2 CD19 BV510 BioLegend 1:100 302242 HIB19
CXCR3 PE-Cy5 BioLegend 1:200 353756 G025H7 CX3CR1 BUV615 BioLegend 1:100 750690 2A9-1 STEP 6: Stain with surface antibodies at room temperature for 30 minutes in BD Brilliant Stain Buffer Plus. Step 1:200 563795 RPA-T8 Marker Fluorophore Supplier Dilution Product number Clone CD8 BUV396 BioLegend 1:200 563795 RPA-T8 CD38 BUV496 BD 1:200 612946 HIT2 LAG3 BUV661 BD 1:200 624285 T47-530 PD-1 BUV737 BD 1:50 612911 EH12.1 CD3 BUV805 BD 1:50 612895 UCHT1 CD14 BV510 BioLegend 1:100 301842 M5E2 CD19 BV510 BioLegend 1:100 302242 HIB19
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STEP 6: Stain with surface antibodies at room temperature for 30 minutes in BD Brilliant Stain Buffer Plus.MarkerFluorophoreSupplierDilutionProduct numberCloneCD8BUV396BioLegend1:200563795RPA-T8CD38BUV496BD1:200612946HIT2LAG3BUV661BD1:200624285T47-530PD-1BUV737BD1:50612791EH12.1CD3BUV805BD1:50612895UCHT1CD14BV510BioLegend1:100301842M5E2CD19BV510BioLegend1:100302242HIB19
Buffer Plus. Fluorophore Supplier Dilution Product number Clone CD8 BUV396 BioLegend 1:200 563795 RPA-T8 CD38 BUV496 BD 1:200 612946 HIT2 LAG3 BUV661 BD 1:200 624285 T47-530 PD-1 BUV737 BD 1:50 612791 EH12.1 CD3 BUV805 BD 1:50 612895 UCHT1 CD14 BV510 BioLegend 1:100 301842 M5E2 CD19 BV510 BioLegend 1:100 302242 HIB19
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CD8BUV396BioLegend1:200563795RPA-T8CD38BUV496BD1:200612946HIT2LAG3BUV661BD1:200624285T47-530PD-1BUV737BD1:50612791EH12.1CD3BUV805BD1:50612895UCHT1CD14BV510BioLegend1:100301842M5E2CD19BV510BioLegend1:100302242HIB19
CD38BUV496BD1:200612946HIT2LAG3BUV661BD1:200624285T47-530PD-1BUV737BD1:50612791EH12.1CD3BUV805BD1:50612895UCHT1CD14BV510BioLegend1:100301842M5E2CD19BV510BioLegend1:100302242HIB19
LAG3BUV661BD1:200624285T47-530PD-1BUV737BD1:50612791EH12.1CD3BUV805BD1:50612895UCHT1CD14BV510BioLegend1:100301842M5E2CD19BV510BioLegend1:100302242HIB19
PD-1 BUV737 BD 1:50 612791 EH12.1 CD3 BUV805 BD 1:50 612895 UCHT1 CD14 BV510 BioLegend 1:100 301842 M5E2 CD19 BV510 BioLegend 1:100 302242 HIB19
CD3 BUV805 BD 1:50 612895 UCHT1 CD14 BV510 BioLegend 1:100 301842 M5E2 CD19 BV510 BioLegend 1:100 302242 HIB19
CD14 BV510 BioLegend 1:100 301842 M5E2 CD19 BV510 BioLegend 1:100 302242 HIB19
CD19 BV510 BioLegend 1:100 302242 HIB19
CD45RA BV570 BioLegend 1:200 304132 HI100
TIM3 BV605 BioLegend 1:100 502936 344823
HLA-DR BV650 BD 1:100 564231 G46-6
IIGII PE-Dazzle594 BioLegend 1:100 3/2/15 A15153G OD407 DD000 DD 4:400 Output UIII 7D M04
CD127 BB030 BD 1:100 Custom HIL-/R-M21 OD07 DV/200 Distance 4:50 000000 00000
CD21 BV/8b BioLegend 1:50 302832 O323 CD4 DE Over 5 Invitragen 4:400 25:0040.00 DMA: 4:5
CD4 PE-Cy5.5 Invitrogen 1:400 35-0042-82 RMA-4.5 CD05 BB700 Biolograph 4:50 205004 DV0
CD90 DD/UU DioLegend 1:50 305034 DX2 CD20 DV/711 DioLegend 1:400 220200 A4

Table S9. Surface and oligo-conjugated antibody staining protocol for single-cellsorting and CITE-seq.

STEP 1: Stain for viability at room temperature for 10 minutes.							
Marker	Fluorophore	Supplier	Dilution	Product	Clone		
	-			number			
LIVE/DEAD	For 405 nm excitation	Invitrogen	1X in	L34957	-		
Fixable		-	PBS				
Aqua							
STEP 2: Stai	n for chemokine receptor	rs at 37°C for [·]	10 minutes.	1			
Marker	Conjugate	Supplier	Dilution	Product	Clone		
				number			
CCR7	TotalSeq-C0148	BioLegend	1:300	353251	G043H7		
CXCR5	TotalSeq-C0144	BioLegend	1:500	356939	J252D4		
CXCR3	TotalSeq-C0140	BioLegend	1:500	353747	G025H7		
CX3CR1	TotalSeq-C0179	BioLegend	1:500	355705	K0124E1		
CCR4	TotalSeq-C0071	BioLegend	1:500	359425	L291H4		
CCR5	TotalSeq-C0141	BioLegend	1:500	359137	J418F1		
CCR6	TotalSeq-C0143	BioLegend	1:500	353440	G034E3		
CXCR6	TotalSeq-C0804	BioLegend	1:500	356023	K041E5		
STEP 3: Stai	n with remaining antibod	ies at room tei	nperature f	or 30 minutes	s in BD Brilliant		
Stain Buffer F	Plus. Use one hashing ar	ntibody per sai	nple.				
Marker	Fluorophore	Supplier	Dilution	Product	Clone		
	-			number			
CD40L	BV421	BioLegend	1:25	310824	24-31		
4-1BB	PE-Cy7	BioLegend	1:25	309818	4B4-1		
CD4	FITC	BD	1:25	345768	SK3		
CD14	BV510	BioLegend	1:100	301842	M5E2		
CD19	BV510	BioLegend	1:100	302242	HIB19		
CD69	BV650	BioLegend	1:50	310934	FN50		
CD8	BV711	BV711 BioLegend		301044	RPA-T8		
Marker	er Conjugate Supplier Diluti		Dilution	Product	Clone		
				number			
CD4	TotalSeq-C0072	BioLegend	1:1250	300567	RPA-T4		
CD8	TotalSeq-C0046	BioLegend	1:10000	344753	SK1		
CD45RA	TotalSeq-C0063	BioLegend	1:4000	304163	HI100		
CD127	TotalSeq-C0390	BioLegend	1:333	351356	A019D5		
CD27	TotalSeq-C0154	BioLegend	1:500	302853	O323		
PD-1	TotalSeq-C0088	BioLegend	1:500	329963	EH12.2H7		
ICOS	TotalSeq-C0171	BioLegend	1:500	313553	C398.4A		
HLA-DR	TotalSeq-C0159	BioLegend	1:500	307663	L243		
CD122	TotalSeq-C0246	BioLegend	1:500	339021	TU27		
CD28	TotalSeq-C0386	BioLegend	1:500	302963	CD28.2		
CD95	TotalSeq-C0156	BioLegend	1:500	305651	DX2		
CD38	TotalSeq-C0389	BioLegend	1:500	303543	HIT2		
CD71	TotalSeq-C0394	BioLegend	1:500	334125	CY1G4		
Hashtag	Conjugate	Supplier	Dilution	Dilution Product Clone			
				number			
Hashtag 1	TotalSeq-C0251	BioLegend	1:100	394661	LNH-94; 2M2		
Hashtag 2	TotalSeq-C0252	BioLegend	1:100	394663	LNH-94; 2M2		
Hashtag 3	TotalSeq-C0253	BioLegend	1:100	394665	LNH-94; 2M2		
Hashtag 4	TotalSeq-C0254	BioLegend	1:100	394667	LNH-94; 2M2		