


Identification and validation of viral antigens sharing sequence and structural homology with tumor-associated antigens (TAAs).

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ABSTRACT

Background The host's immune system develops in equilibrium with both cellular self-antigens and non-self-antigens derived from microorganisms which enter the body during lifetime. In addition, during the years, a tumor may arise presenting to the immune system an additional pool of non-self-antigens, namely tumor antigens (tumor-associated antigens, TAAs; tumor-specific antigens, TSAs).

Methods In the present study, we looked for homology between published TAAs and non-self-viral-derived epitopes. Bioinformatics analyses and ex vivo immunological validations have been performed.

Results Surprisingly, several of such homologies have been found. Moreover, structural similarities between paired TAAs and viral peptides as well as comparable patterns of contact with HLA and T cell receptor (TCR) α and β chains have been observed. Therefore, the two classes of non-self-antigens (viral antigens and tumor antigens) may converge, eliciting cross-reacting CD8⁺ T cell responses which possibly drive the fate of cancer development and progression.

Conclusions An established antiviral T cell memory may turn out to be an anticancer T cell memory, able to control the growth of a cancer developed during the lifetime if the expressed TAA is similar to the viral epitope. This may ultimately represent a relevant selective advantage for patients with cancer and may lead to a novel preventive anticancer vaccine strategy.

INTRODUCTION

Therapeutic cancer vaccines have been developed and evaluated in clinical trials targeting different tumor settings and involving thousands of patients with cancer. The observed overall rate of clinical benefit is a rather disappointing 20%.^{1–6}

One of the factors responsible for such limited efficacy is represented by the quality of target tumor antigens identified over the years and included in the vaccine (<https://caped.icp.ucl.ac.be/Peptide/list>).⁷ Indeed, tumor antigens need to be sufficiently distinct

from self-antigens to break the immunological tolerance that physiologically blocks undesired autoimmune reactivity against normal cells.

Tumor-associated antigens (TAAs) are shared among patients with the same malignancy.^{8–11} They include different type of antigens, namely aberrantly overexpressed self-antigens in tumor cells compared with normal cells, cell lineage differentiation antigens, which are normally not expressed in adult tissue^{12–14} and cancer/germline antigens (also known as cancer/testis), which are normally expressed only in immune-privileged germline cells.^{15–19}

Consequently, the main drawback of using overexpressed or cell lineage differentiation TAAs in cancer immunotherapy is the induction of T cells with low-affinity receptors (TCRs), which are unable to mediate effective antitumor responses.^{20–21} Alternatively, they may be unable to elicit an immune response given that T cells specific for these self-antigens may have been removed from the immune repertoire by central and peripheral tolerance.²²

To improve the immunogenicity of TAAs, peptides have been modified (heteroclitic peptides) to increase their affinity and binding to the Major Histocompatibility Complex (MHC)-I.²³ Such modified peptides have been shown to break the immunological tolerance, inducing a more potent CD8⁺ T cell response able to recognize the native peptide and kill tumor cells.^{24–28} Indeed, it has been proven that TCRs are able to cross-react with multiple pMHCs characterized by narrow sequence differences.^{29–31}

An alternative strategy would be the identification of natural analog peptides, sharing

sequence homology with TAAs and able to induce T cells with cross-reacting TCRs for an improved antitumor cytotoxic effect.

In this respect, scattered data suggest that antigens derived from pathogens (pathogen-associated antigens, PaAs) may share sequence homology with TAAs and elicit cross-reacting CD8⁺ T cell responses, driving the fate of cancer development, progression and eventually response to therapy. Different research groups have reported that patients with cancer with tumor lesions expressing tumor antigens with high similarity to pathogens may have a better clinical outcome.^{32–36} We have recently shown that mutated neoantigens may show >50% sequence similarity to PaAs and the central TCR-facing residues can be identical. Paired neoantigens and PaAs were shown to elicit cross-reacting T cells in immunized mice and to be cross-recognized by peripheral blood mononuclear cells (PBMC) from a long-term surviving patient with hepatocellular carcinoma (HCC).³⁷ Furthermore, mice prevaccinated with viral epitopes with high similarity to tumor epitopes have been shown to better control tumor growth compared with naïve mice.

Based on such reported observations, and considering the large number of non-self-PaAs to which humans are exposed during their lifetime, we screened all the TAAs described in the literature and publicly available at cancer peptide database (<https://caped.icp.ucl.ac.be/Peptide/list>) for sequence homology to viral sequences. Surprisingly, several such homologies have been found. Moreover, structural similarities between paired TAAs and viral peptides as well as comparable patterns of contact with HLA and TCR α and β chains have been observed. Therefore, viral antigens and tumor antigens may elicit cross-reacting CD8⁺ T cell responses and an antiviral T cell memory may be able to control the growth of a cancer developed during the lifetime, if the expressed TAA is similar to the viral epitope. This may ultimately represent a relevant selective advantage for patients with cancer and may lead to a novel preventive anticancer vaccine strategy.

MATERIALS AND METHODS

Epitope prediction analysis

All the peptides selected in the study were predicted with the NetMHCpan V.4.1 and the NetMHCstabpan V.1.0 predictive algorithms (<https://services.healthtech.dtu.dk/service.php?NetMHCpan-4.1>; <https://services.healthtech.dtu.dk/service.php?NetMHCstabpan-1.0>).

The peptides deposited at the cancer antigenic peptide database (<https://caped.icp.ucl.ac.be/Peptide/list>) were used to interrogate NetMHCpan V.4.1 tool.³⁸ Nanomer peptides for the four most prevalent MHC class I HLA-A*0101, 0201, 0301 and 2402 alleles (<http://www.allele-frequencies.net>) have been selected with a predicted affinity value <100 nM (strong binders, SBs).

Likewise, viral nanomer peptides identified by the Basic Local Alignment Search Tool (BLAST) homology search were used to interrogate NetMHCstabpan V.1.0 tool³⁹ for the four most prevalent MHC class I HLA-A*0101, 0201,

0301 and 2402 alleles. SB peptides were selected with a predicted affinity value <100 nM and stability >1 hour.

BLAST homology search

The TAAs selected as SB according to NetMHCpan V.4.1 prediction tool have been submitted to BLAST for a protein homology search against viral sequences (Viruses—taxid:10239) within the non-redundant protein sequences database (<https://blast.ncbi.nlm.nih.gov/Blast.cgi>). Homologous viral protein sequences have been extracted from the protein database of the National Center for Biotechnology Information (<https://www.ncbi.nlm.nih.gov/>) and epitope prediction has been performed with the NetMHCstabpan V.1.0 tool.

Epitope modeling and molecular docking

The 1A07 complex was selected from the protein data bank which includes the structure of the HTLV-I LLFGYPVYV peptide crystallized with the HLA-A*0201 molecule, the β 2 microglobulin, the α and β chains of the TCR (PDB <https://www.rcsb.org/structure/1A07>). The PyMol software (PyMol Molecular graphics system, V.1.8.6.2) was used to modify the TAX peptide sequence into the peptides analyzed in the present study. The Molsoft Mol Browser (version 3.8-7d) was used to generate the epitope modeling and molecular docking.

IFN- γ ELISpot assay

IFN- γ ELISpot (BD human IFN- γ ELISPOT Set) assay was performed on PBMCs from HLA-A*0201 healthy subjects. 4×10^6 PBMCs/mL/well were stimulated ex vivo with viral peptides at a final concentration of 10 μ g/mL. In particular, MLGTHAMLV (Cytomegalovirus(CMV)), ILDCVLVHL (human papillomavirus (HPV)) and IIGALVGV (HIV) viral peptides were used for the ex vivo stimulation. On day three, 10 U/mL IL-2 was added to each well. On day five, half of the volume of medium was replaced with fresh medium containing IL-2 at a final concentration of 10 U/mL. On day seven, PBMCs were restimulated with each peptide. On day 10, cells were harvested for IFN- γ ELISpot assay. Paired TAA peptides MLGTHAMLV (gp100), ILDKVLVHL (Caseinolytic Mitochondrial Matrix Peptidase Proteolytic Subunit (CLPP)) and IMIGVLVGV (Carcinoembryonic antigen (CEA)) were added at a final concentration of 10 μ g/mL to 2×10^5 PBMCs per well in 100 μ L RPMI 1640 medium (Capricorn Scientific GmbH). PBMCs were cultured at 37 °C in a humidified incubator with 5% CO₂ for 20 hours. Stimulation with 10 μ g/mL Phytohemagglutinin (PHA-K; Capricorn Scientific GmbH) was used as positive control, PBMCs without added peptides were used as the negative control, RPMI 1640 medium (Capricorn Scientific GmbH) was used as background control. The plates were read with an AID EliSpot Reader Systems (AID GmbH, Strassberg, Germany). Determinations from triplicate tests were averaged. Data were analyzed by subtracting the mean number of spots in the wells with cells and medium-only from the mean counts of spots in wells with cells and

antigen. Spot forming units (SFU) were calculated as the frequency per 10^6 PBMCs.

The computational model

The computational model C-IMMSIM derives from a general-purpose simulation platform that suitably characterizes the role of the immune response in different human pathologies such as infections, cancer, hypersensitivity, and inflammation. The model integrates the *primary sequences* of TCRs, BCRs, paratopes, peptides and epitopes of the antigen (eg, a virus or a tumor antigenic determinant). It exploits immunoinformatics tools to calculate B-cell epitopes and TCR peptides of antigenic sequences, and a generic contact potential to estimate the affinity between T-cells receptors and peptides presented by antigen-presenting cells, infected cells, or, as in the present case, malignant (tumor) cells.^{40 41} Besides that, the model accepts in input any pre-calculated list of peptides associated with a “ranked likelihood” to bind a certain HLA,⁴² for example, NetMHCstabpan.³⁹ Moreover, an arbitrary value is introduced in the modeling to evaluate the conformational similarity between the paired peptides. In the present study, a number of malignant cells (10^3 cells) are set in the simulated volume (about 10 μ L) at the beginning of the simulation (ie, day 0). These cells promptly start to duplicate (population doubling time of about 80 hours) and, in absence of therapy, they would reach a limiting value determining the interruption of the simulation (this limiting value is set to 3.4×10^5 cancer cells/ μ L).

The vaccination protocol consists of five injections of paired peptides formulated with a generic “virtual” adjuvant whose unique effect is to activate innate immune cells. The vaccine administration protocol is shown in online supplemental figure 4. The results refer to simulations of 80 days of virtual time post-tumor implantation.

RESULTS

Blast search for homology between tumor antigens and viral sequences

Peptides from the cancer antigenic peptide database (<https://caped.icp.ucl.ac.be/Peptide/list>) were used to interrogate the NetMHCpan predictive algorithm. Predicted SBs restricted to the most frequent MHC class I alleles were selected (nr. 99) with a binding affinity value <100 nM. The vast majority of such SB were identified for the HLA-A*0201 (75 out 99, 75.7%) and 41/75 were identified in the “overexpressed” subgroup (table 1).

In order to identify homologous viral sequences, all the predicted SB TAAs were subjected to global protein BLAST against the virus sequences within the GeneBank non-redundant protein database. The search returned a large number ($n=82$) of viral sequences sharing homology with the TAAs and the vast majority ($n=75$) were HLA-A*0201 restricted. Interestingly, the virus sharing the highest number of sequences with TAAs is the HIV type 1 (HIV-1) (36/82),

followed by the Herpesviruses (22/82) and by the human papillomaviruses (9/82) (table 2).

Epitope prediction for the viral sequences

All the 82 viral sequences identified through the BLAST search, sharing sequence homology with the TAAs, were used to interrogate the NetMHCstabpan predictive algorithm. The results showed that only a limited number of such viral sequences (nr. 20) are predicted to be SBs to the corresponding MHC-class I alleles, and 9/20 sequences (45%) are derived from HIV-1. Affinity values are significantly lower than 100 nM and in most cases lower than 50 nM, which are comparable to those of the corresponding TAAs (table 3). Furthermore, the algorithm predicts an average binding stability of the viral sequences, expressed in hours, which is lower than the one predicted for the TAAs (6.01 hour vs 10.3 hour) but does not reach the statistical significance (table 3 and online supplemental figure 1). Overall, with the exception of few pairs with the viral sequences having suboptimal values of affinity and stability, all the others show predicted values of the highest biological relevance (figure 1).

Epitope modeling and molecular docking

In order to verify that predicted paired TAA and viral epitopes share similar contact residues with both the HLA molecule and the TCR, epitope modeling and molecular docking were performed for each paired peptides. This was possible only for HLA-A*0201 restricted epitopes, due to the lack of crystallized structures including both HLA and TCR for other alleles deposited in the PDB. Epitopes crystallized with the HLA-A*0201 and the TCR showing sequence homology with TAA peptides were not found. Therefore, fully aware of the possible caveats, the IAO7 crystallized complex including the HTLV-I TAX epitope was used as general template to conduct the analyses.

CLPP versus E1 HPV

The *ILDCVLVHL* E1 HPV peptide is predicted to have a higher affinity (12.9 vs 24.98 nM) and a similar stability (5.36 vs 6.54 hours) than the *ILDKVLVHL* CLPP peptide. The interacting pattern between the residues of both peptides and the HLA as well as the β chain of the TCR is identical. The only difference is represented by the difference in position 4 of the basic K with a polar C residue, which substantially changes the contact pattern with the α chain of the TCR (figure 2A). This would suggest that the TCR clones targeting the two peptides would share only the same β chain. Furthermore, the pattern of hydrogen bonds observed in the paired peptides is extremely similar with identical distances between the interacting residues. However, only the HPV peptide shows two bonds between the L2 residue and the HLA K66 as well as the TCR α chain Q30, supporting the higher affinity to the HLA molecule and suggesting a limited T cell cross-reactivity (online supplemental figure 2A).

Table 1 Affinity prediction for tumor-associated antigens from the cancer antigenic peptide database									
Mutation	Tumor specific			Differentiation			Overexpressed		
	Seq	Aff (nM)	Seq	Aff (nM)	Seq	Aff (nM)	Seq	Aff (nM)	Seq
HLA-A*0201									
FLDEFMEGV	2.86	MLAVISCAV	6.18	IMIGVLVGV	3.61	FMNKFYEI	2.34		
VMSWAPPV	5.04	KVLEYVIKV	6.23	RLMKQDFSV	4.23	RLMNDMTAV	3.39		
GLFGDIYLA	6.07	GLYDGMIEHL	7.91	YMDGTMSQV	5.06	RLAPFVYLL	3.57		
LLDDELLVSI	7.09	FLWGPRALV	8.25	MLGTHTMEV	7.3	FLLGLIFLL	3.81		
ILDKVLVHL	23.6	KVAELVHFL	12.85	MLLAVLYCL	9.16	LLNAFTVTV	4.62		
FLIHWQNTM	41.32	KASEKIFYV	19.14	KTWGQYWQV	10.05	FLGYLILGV	4.72		
ILNAMIAKI	48.98	KWVEFLAML	28.91	YLSGANLNL	11.01	RLVDDFLLV	5.33		
RLSSCPVA	95.1	FLDRFLSCM	29.39	SLSKILDTV	11.3	ILAKFLHWL	6.69		
		MLMAQEALA	36.44	TLMSAMTNL	14.16	SLLSGDWWL	9.08		
		ALSVMGVYV	39.45	LLWSFQ TSA	15.49	ALLALTSAV	9.8		
		SLGWLFLLL	62.17	SVYDFFVWL	30.44	RMPEAAPPV	9.87		
				TLDSQVMSL	40.15	SLLQLHLGL	10.34		
				FLFLFFWL	42.03	LLGATCMFV	10.56		
				YLEPGPVA	90.62	ALWPWLLMA	11.75		
				VLHWDPEV	93.14	LLGRNSFEV	12.27		
						KIFGSLAFL	12.97		
						FMVEDETVL	16.5		
						MIAVFLPIV	19.54		
						FVGEFFTDV	19.75		
						TLNDECWPA	20.02		
						VLDGLDVLL	22.43		
						TLPGYPPHV	23.06		
						LLLLTLTV	23.85		
						CQWGRLWQL	24.33		
						ALLEIASCL	26.78		
						FLALSILV	30.04		
						RLLETETLV	30.47		
						ILHNGAYSL	30.71		
						VLPPPLPSL	30.78		
						LLSDDVVV	32.87		

Continued

Table 1 Continued									
Mutation		Tumor specific		Differentiation		Overexpressed			
Seq	Aff (nM)	Seq	Aff (nM)	Seq	Aff (nM)	Seq	Aff (nM)	Seq	Aff (nM)
		VLGVVFGI							33.45
		KMDAEHPPEL							35.44
		CIAEQYHTV							48.36
		HLSTAFARV							49.81
		TIHDSIQYV							50.48
		KVHPVIWSL							57.52
		VLCSIDWFM							58.74
		GLPPDVQRV							64.57
		SVASTITGV							70.61
		MIMVKCWMI							74.82
		GLQLGVQAV							77.31
HLA-A*2402									
SYLDSGIHF	30.15	LYATVHDI	36.85	IYMDGTADF	11.17	KYDCFLHPF			21.58
		NYKRCFPVI	76.24	AFLPWHRLF	36.32	LYVDSLFFL			73.72
				TYACFVSNL	43.49	NYARTEDFF			100.71
				VYFFLPDHL	47.11				
HLA-A*0101									
YTDFHCQYV	20.14	EVDPIGHLY	20.91	N/A		N/A			
YVDFREY	11.2	EADPTGHSY	71.37						
HLA-A*0301									
KINKNPKYK	55.3	SLFRAVITK	12.2	HLFGYSWYK	6.17	NTYASPRFK			29.97
				LIYRRRLMK	7.81	VLRENTSPK			31.21
				ALNFPQSQK	15.05	LASFKSFLK			90.6
				ALLAVGATK	38.81				
				RSYVPLAHR	64.02				

Table 2 Continued

HLA-A*0201

Mutation	Tumor specific		
LLLLTLTV	LLLLTLTV	ORF46 (human gammaherpesvirus 8)	
CQWGRWLWQL	DEWASLWXW	Envelope glycoprotein, partial (HIV 1)	
FLALSILVL	YLALSVLTV	Vif protein (HIV 1)	
	FLALSIVNR	Envelope glycoprotein (HIV 1)	
RLLQETELV	RLLQQTEVY	E6 (human papillomavirus type 39)	
	LLLQETEVI	Envelope glycoprotein, partial (HIV 1)	
ILHNGAYSLSL	ILXNGXYSL	Truncated pol protein, partial (HIV 1)	
	ILXNGQYSL		
	YYHNGAYS	Envelope glycoprotein (HIV 1)	
VLVPPPLPSL	DQVPPPLPSL	Gag protein, partial (HIV 1)	
	KEIPPLPSL	Gag protein, partial (HIV 1)	
	DREPPLPSL	Gag protein (HIV 1)	
LLSDDDDWW	SLAEDDDWW	Envelope glycoprotein, partial (HIV 1)	
KMDAEHPPEL	RMDAHPGL	Polymerase PB1 (influenza B virus)	
	KMDEEHPGL	Polymerase PB1 (influenza B virus (B/Ann Arbor/1994))	
	VFDPPELPEL	DNA polymerase (human mastadenovirus D, human adenovirus 63)	
CIAEQYHTV	SAAEAYHTV	Small hydrophobic protein (human metapneumovirus)	
HLSTAFARV	LLSTAFARW	Protein UL150 (human betaherpesvirus 5)	
	LLSTAFAIW	Protein UL150 (human betaherpesvirus 5)	
TIHDSIQYV	QIHDRIQYV	BALF5 (human gammaherpesvirus 4)	
KVHPVWVSL	SVHPVWLWNC	ORF4a protein (human betacoronavirus 2c Jordan-N3/2012)	
MIMVKCWMI	TQEVKCVWMT	p24, partial (HIV 1)	
	MIMVKGIPK	Envelope glycoprotein O (human betaherpesvirus 5)	
	MIMVKVGGQ	Pol protein, partial (HIV 1)	
	DIMVKCYLA	DNA polymerase (human mastadenovirus C)	
HLA-A24:02			
Mutation	Tumor specific		
TAA	TAA	Blast Seq	Virus
SYLDSGIHF	TYLDNGVHV	L2 protein human papillomavirus 204	
Differentiation	Overexpressed		
TAA	TAA	Blast Seq	Virus
N/A	NYARTEDFF	LYKRTEDFW	Reverse transcriptase, partial (HIV 1)

Continued

Table 3 Affinity and stability prediction for the paired peptides for the paired peptides PLEASE ALSO IN THIS TABLE CHANGE COMMAS WITH DECIMAL DOT

HLA	Epitope seq	Affinity (nM)	TAA	Class	Tumor	Pathogen	ID seq
A*02:01	ILDKVLVHL	23,6	CLPP	Mutation	Melanoma	L1 capsid protein (HPV)	AEQ98783.1
	ILEKVVHVL	378,08				E1 protein (HPV)	AYA94830.2
	ILDCVLVHL	12,61					
A*03:01	ILDAWAQK	131,69	EFTUD2	Mutation	Melanoma	Non-structural protein (Chikungunya virus)	AND80849.1
	IIDAWSQK	117,57					
A*24:02	NYKRCFPVI	76,24	MAGE-A4	Tumor specific	Multiple	Human rotavirus A	CAA54177.1
	NYKKCPKI	118,22					
A*02:01	IMIGVLVGV	3,61	CEA	Differentiation	Gut ca		
	IMVGALIGV	4,86				Env protein (HIV-1)	ALF12185.1
	IIIGALVGV	8,04				Env protein (HIV-1)	AAL98851.1
A*02:01	MLGTHTMEV	7,3	gp100	Differentiation	Melanoma	Membrane protein UL20 HHV5	AKI23125.1
	MLGTHAMLV	12,6					
A*02:01	MLLAVLYCL	9,16	Tyrosinase	Differentiation	Melanoma		
	NLLAVLYCV	6,18				Gag protein (HIV-1)	AAA45294.1
	NTLAVLYCV	38,61				Gag protein (HIV-1)	AAS45421.1
	MLLAALMIV	5,38				Env protein (HERVK)	CAA76880.1
A*03:01	ALNFPGSQK	15,05	Gp100	Differentiation	Melanoma	Pol (HIV-1)	AWT86382.1
	ALNFPGKWK	36,42					
A*02:01	RLMNDMTAV	3,39	HSPH1	Overexpressed	Ubiquitous	Large tegument protein (HSV-2)	AMB66144.1
	RLADDMTSV	5,65					
A*02:01	RLAPFVYLL	3,57	HEPACAM	Overexpressed	LIVER	polyprotein (Hlyuisk human encephalomyelitis virus)	ACG55801.1
	RLAPFGYKI	24,96					
A*02:01	LLNAFTVTV	4,62	CD274	Overexpressed	Multiple tissues	Env protein (HIV-1)	AXP14971.1
	LLNAFAIAV	8,96					
A*02:01	RLVDDFLV	5,33	Telomerase	Overexpressed	Multiple tissues		
	RLVDEFLAI	18,98				Env protein (HIV-1)	AKR69573.1
	RLVNDFLAL	30,13				Env protein (HIV-1)	ASN74133.1
A*02:01	LLLLTLTV	23,85	MUC1	Overexpressed	Gland epithelial	ORF46 (HHV8)	QKE51297.1
	LLLNTVLTV	5,88					
A*02:01	LLSDDDDWW	32,87	KIF20A	Overexpressed	Ubiquitous		
	SLAEDDDWW	33,9				Env protein (HIV-1)	QCC27033.1

Continued

Table 3 Continued

A*02:01	KMDAEHPEL RMDAEHPGL KMDEEHPGL	35,44 94,22 20,99	Secernin 1	Overexpressed	Ubiquitous	Pol PB1 (influenza B virus) Pol PB1 (influenza B virus)	AXA17413.1 ABL77000.1
A*03:01	LASFKSFLK LAAFKSFLK	90,6 78,01	RGS5	Overexpressed	Ubiquitous	E1 (HPV 57)	BAF80482.1

TAA, tumor-associated antigen.

encephalomyelitis virus peptide compared with the HEPACAM peptide (online supplemental figure 2D).

CD274 versus ENV HIV

The *LLNAFAIAV* Env HIV peptide is predicted to have high but lower affinity (8.96 vs 4.62 nM) and a good but lower stability (11.15 vs 23.08 hours) than the *LLNAF-TVTV* CD274 peptide. The interacting pattern between the residues of both peptides and the HLA as well as the α and β chains of the TCR is identical. Interestingly, the polar to non-polar T-A mismatch at positions 6 and 8 as well as the conservative non-polar residues (I7V) do not change the contact pattern (figure 2E). This would suggest that the TCR clone targeting the two peptides would share the same α and β chains. Furthermore, the pattern of hydrogen bonds observed in the paired peptides is extremely similar with identical distances between the interacting residues. The only difference is the missing A8 – HLA D77 bond which would explain the lower affinity and stability to the HLA of the Env HIV peptide compared with the CD274 peptide (online supplemental figure 2E).

MUC1 versus ORF46 HHV8

The *LLLNTVLTV* ORF46 HHV8 peptide is predicted to have a higher affinity (5.88 vs 23.85 nM) with higher stability (13.11 vs 6.69 hours) than the *LLLLTVLTV* MUC1 peptide. The only mismatch along the sequence between the two peptides is the non-conservative polar to non-polar residue N to L at position 4. The contact pattern between the residues of the peptides and the HLA as well as the β chain of the TCR is identical. On the contrary, the contact pattern with the α chain of the TCR is substantially different, suggesting that the TCR clone targeting the peptides would share the same β chain and a different α chain (figure 2F). The pattern of hydrogen bonds observed in the paired peptides shows a missing L2 – HLA K66 bond in the HHV8 peptide and two missing L2 – TCR α chain Q30 as well as T8 – HLA D77 bonds in the MUC1 peptide. All other bonds show no deviation in the distances. Such a pattern of hydrogen bonds may explain the higher affinity and stability to the HLA of the HHV8 peptide compared with the MUC1 peptide (online supplemental figure 2F).

KIF20A versus Env HIV

The *SLAEDDVVV* Env HIV peptide is predicted to have a high and similar affinity (33.9 vs 32.87 nM) with similar stability (1.84 vs 2.41 hours) than the *LLSDDDVVV* KIF20A peptide. The mismatches along the sequence between the two peptides are the non-conservative polar to non-polar S1L and A3S residues as well as the conservative acidic E5D residues. The contact pattern between the residues of the peptides and the HLA as well as the β chain of the TCR is identical. On the contrary, the contact pattern with the α chain of the TCR is substantially different, suggesting that the TCR clone targeting the peptides would share

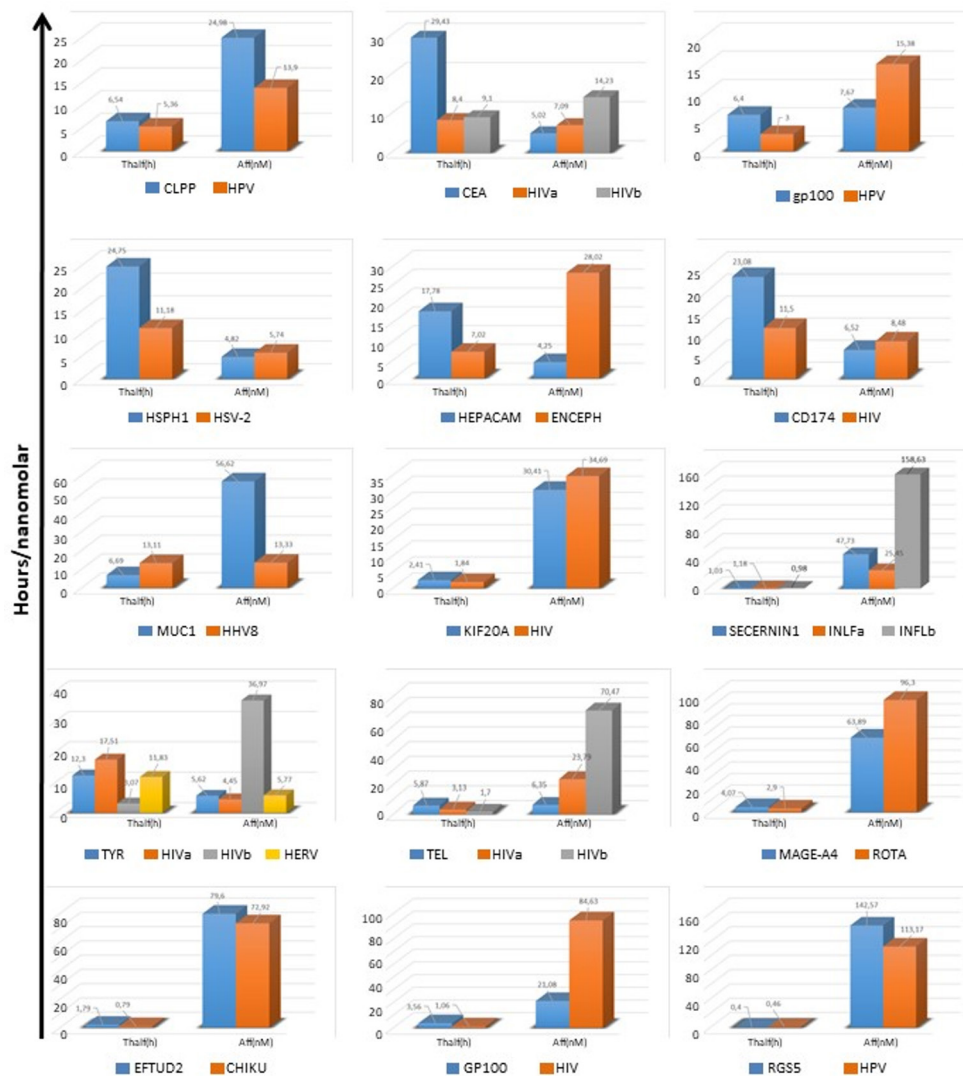


Figure 1 Affinity and stability of paired peptides. The affinity and stability to corresponding HLA molecules were predicted by NetMHCstabpan for each viral and tumor-associated antigen paired peptides. The stability (Thalf) values are expressed in hours (h); the affinity (Aff) values are expressed in nanomolarity (nM).

the same β chain and a different α chain (figure 2G). The pattern of hydrogen bonds observed in the paired peptides shows three missing bonds in the KIF20A peptide, namely L2 – HLA K66, L2 – TCR α chain Q30 and A3 – HLA Y99. All other bonds show minor deviations in the distances. Nevertheless, the affinity and stability to the HLA of the two peptides are similar (online supplemental figure 2G).

Tyrosinase versus Gag HIV and Env HERV

The *NLLAVLYCV*Gag HIV peptide and the *MLLAALMIV* Env HERV peptide are predicted to have a very high and similar affinity (6.18 and 5.38 vs 9.16 nM) with high and similar stability (17.51 and 11.83 vs 12.3 hours) than (shouldn't be to?) the *MLLAVLYCL* tyrosinase peptide. The two mismatches along the sequence between the Gag HIV and tyrosinase peptides are conservative non-polar residues (L9V) and non-conservative polar to non-polar (N1M). This does not substantially change the contact pattern between the residues of the peptides

and the HLA as well as the β chain of the TCR, with a minor change in the contact pattern with the α chain. This would suggest that the TCR clone targeting the peptides would share the same chains. The mismatches along the sequence between the Env HERV and tyrosinase peptides are conservative non-polar (A5V and V9L) and non-conservative polar to non-polar residues (M7Y and I8C). This does not substantially change the contact pattern between the residues of the peptides and the HLA as well as the α chain of the TCR. On the contrary, the contact pattern with the β chain of TCR shows a substantial change. This would suggest that the TCR clone targeting the peptides would share the same α chains but different β chains (figure 2H). Furthermore, the pattern of hydrogen bonds observed in the paired peptides is extremely similar with identical distances between the interacting residues with minor deviations. The only exception for the Env HERV peptide is the missing M1 – HLA Y159 bond, although this does not

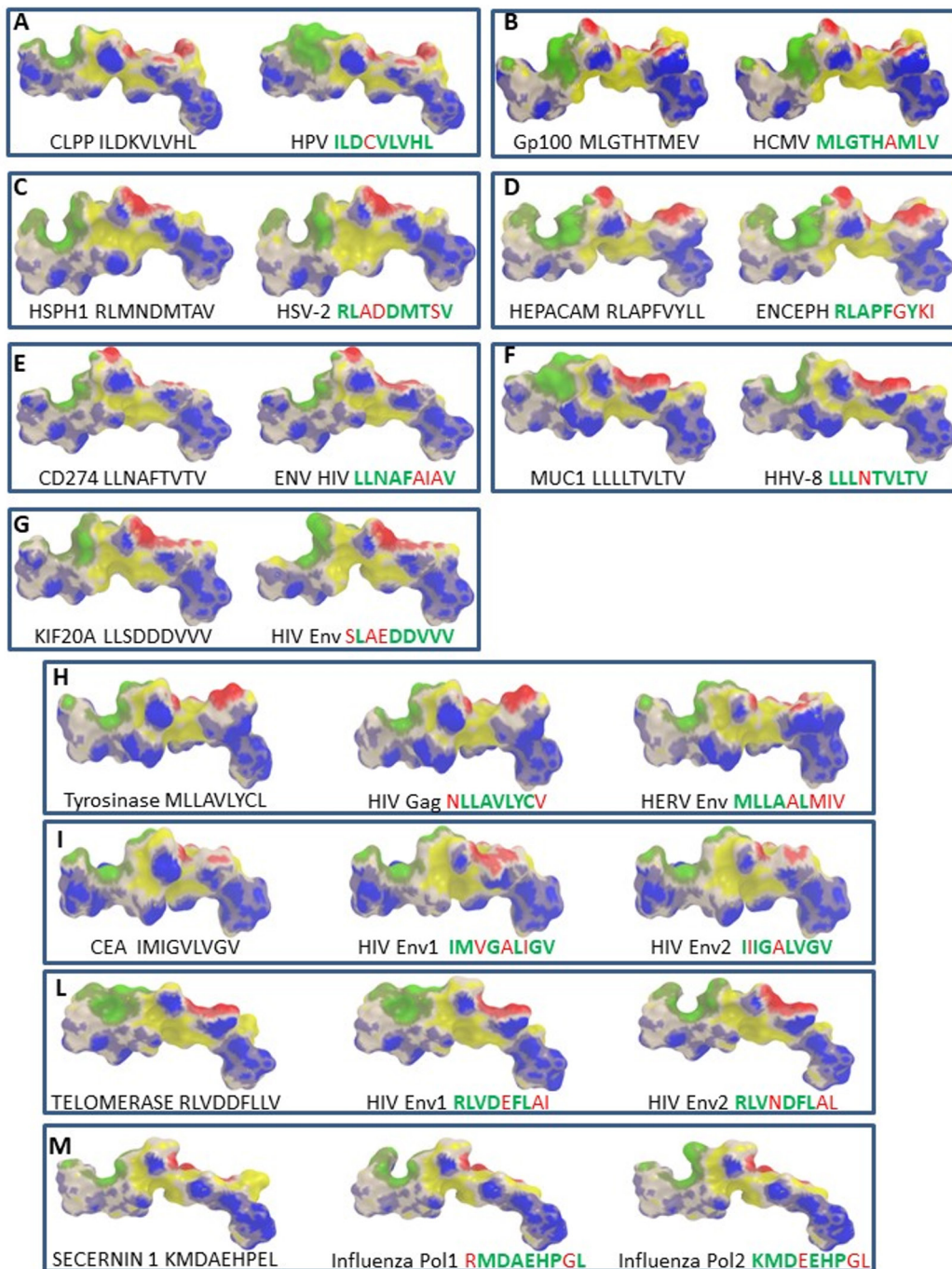


Figure 2 Structural predicted conformation of paired peptides. The conformation of the paired viral and tumor-associated antigen peptides bound to the HLA-A*02:01 molecule is shown. The prediction was performed using as template structure the HTLV-I LLFGYPVYV peptide crystallized with the HLA-A*0201 molecule, the β 2 microglobulin, the α and β chains of the T cell receptor (TCR) (PDB <https://www.rcsb.org/structure/1AO7>). Blue areas = contact points with HLA molecule; Red areas=contact points with the TCR α chain; Green areas=contact points with the TCR β chain.

impact neither on the affinity nor on the stability to the HLA compared with the Gag HIV and the tyrosinase peptides (online supplemental figure 2H).

CEA versus Env HIV

The *IMVGALIGV* Env1 and *IIIGALGVV* Env2 HIV peptides are predicted to have a very high and similar affinity (4.86 and 8.04 vs 3.61 nM) with high but lower stability (8.4 and 9.1 vs 29.43 hours) than the *IMIGVLGV* CEA peptide.

The mismatches along the sequence between the Env HIV and CEA peptides are all conservative non-polar residues. This does not substantially change the contact pattern between the residues of the peptides and the HLA as well as the α and β chains of the TCR, suggesting that the TCR clone targeting the peptides would share the same chains. In particular, the Env2 HIV peptide shows the highest similarity with the CEA peptide (figure 2I). Furthermore,

the pattern of hydrogen bonds observed in the paired peptides is extremely similar with identical distances between the interacting residues. The only exception for the Env1 peptide is the more distant V3 – HLA Y99 bond; for the Env2 peptide the missing I1 – HLA Y159 bond and the closer I2 – HLA E63 bond. The latter differences may support the lower affinity value to the HLA of the Env2 peptide compared with the Env1 and the CEA peptides (online supplemental figure 2I).

Telomerase versus Env HIV

The *RLVDEFLAI* Env1 and *RLVNDFLAL* Env2 HIV peptides are predicted to have a high but lower affinity (18.98 and 30.13 vs 5.33 nM) with good but lower stability (3.13 and 1.7 vs 5.87 hours) than the *RLVDDFLLV* Telomerase peptide. The mismatches along the sequence between the Env1 HIV and Telomerase peptides are conservative non-polar (A8L and I9V) and conservative acidic residues (E5D). This does not substantially change the contact pattern between the residues of the peptides and the HLA as well as the α and β chains of the TCR. This would suggest that the TCR clone targeting the peptides would share the same chains. On the contrary, the mismatches along the sequence between the Env2 HIV and Telomerase peptides are conservative non-polar (A8L and L9V) and non-conservative polar to acidic residues (N4D). The latter has a substantial change in the contact pattern between the residues of the peptides and the α and β chains of the TCR, suggesting that the TCR clones targeting the peptides would be different (figure 2L). Furthermore, the pattern of hydrogen bonds observed in the paired Env1 HIV and the telomerase peptides shows a deviation in the distance between the D4 – TCR α chain S100 residues. On the contrary, the pattern of hydrogen bonds observed in the paired Env2 HIV and the Telomerase peptides shows a deviation both in the distances in the D4 – TCR α chain S100 as well as in the R1 – HLA Y159 residues. The latter deviations in the pattern of hydrogen bonds may explain the substantially lower affinity and stability to the HLA of the Env1 peptide compared with the Env2 HIV and the Telomerase peptides (online supplemental figure 2L).

Secernin1 versus PolB1 influenza

The *RMDAEHPGL* Inf11 peptide is predicted to have a lower affinity (94.22 vs 35.44 nM) while the *KMDEEHPGL* Inf12 peptide is predicted to have a higher affinity (20.99 vs 35.44 nM) with similar stability (1.18 and 0.98 vs 1.03 hours) to the HLA than the *KMDAEHPGL* Secernin 1 peptide. The mismatches along the sequence between the Inf11 and Secernin 1 peptides are conservative basic residues (R1K) and non-conservative non-polar to acidic residues (G8E). This does not substantially change the contact pattern between the residues of the peptides and the HLA as well as the β chain of the TCR, while the contact pattern with the α chain of the TCR is severely affected. This would suggest that the TCR clone targeting the peptides would share the same β chain but different

α chains. On the contrary, the mismatches along the sequence between the Inf12 and Secernin 1 peptides are non-conservative non-polar to acidic residues (A4E and G8E). This does not substantially change the contact pattern between the residues of the peptides and the HLA as well as the β chain of the TCR, while the contact pattern with the α chain of the TCR is slightly affected. This would suggest that the TCR clone targeting the peptides would share the same β chain but different α chains (figure 2M). Furthermore, the pattern of hydrogen bonds shows a missing bond in the Inf12 and Secernin 1 peptides, namely L2 – HLA K66; a missing bond in the Inf11 and Inf12 peptides was observed, namely L9 – HLA T143. Moreover, a significant deviation was observed in the in the distance between A4 – TCR α chain bond of the Inf12 peptide. These differences in the hydrogen bonds may explain the affinity and stability to the HLA observed for the two Influenza peptides compared with the Secernin 1 peptide (online supplemental figure 2M).

Ex vivo cross-reactivity to viral antigens and TAAs

A cross reactive immunity between paired HLA-A*02:01 restricted viral epitopes and TAAs was verified ex vivo using PBMCs from HLA-A*02:01 subjects. In order to simulate how an in vivo preimmunization to viral antigens might cross-react to a paired TAA expressed by cancer cells, PBMCs were “immunized” ex vivo with each of the selected viral peptides. After 14 days, the IFN γ ELISpot assay was then performed by restimulating in parallel with the “vaccine” viral peptide or the paired TAA peptide. The first observation was that individual subjects had variable levels of circulating T cells reacting to the viral peptides, with the strongest reactivity against the HPV ILDCVLVHL peptide and a significantly weaker reactivity against the CMV MLGTHAMLV and HIV IIIGALVGV peptides. The reactivity against the latter two peptides was not statistically different (figure 3A,B). Considering that the three viral peptides show comparable binding affinity, stability and T-cell propensity prediction scores, such a different IFN γ production could be explained by the expansion ex vivo of a pre-existing immunological memory to the HPV peptide. Strikingly, restimulation with paired TAA peptides induced a T cell cross-reactivity in all three settings, with inter-subject variation (online supplemental figure 3). Overall, gp100 and CEA TAA peptides induced an IFN γ production not statistically different from the paired viral peptides, CMV and HIV-1 respectively. On the contrary, restimulation with CLPP peptides induced a T cell response which was significantly lower than the HPV paired peptide (113 vs 802 SFU $\times 10^6$ cells) (figure 3C). Interestingly, although binding affinity, stability and T-cell propensity prediction scores were similar between the three paired peptides, the structural conformation of the HPV and CLPP paired peptides showed a significant discordance (figure 2A). The latter observation could explain the lower T cell cross-reactivity induced by these two paired peptides.

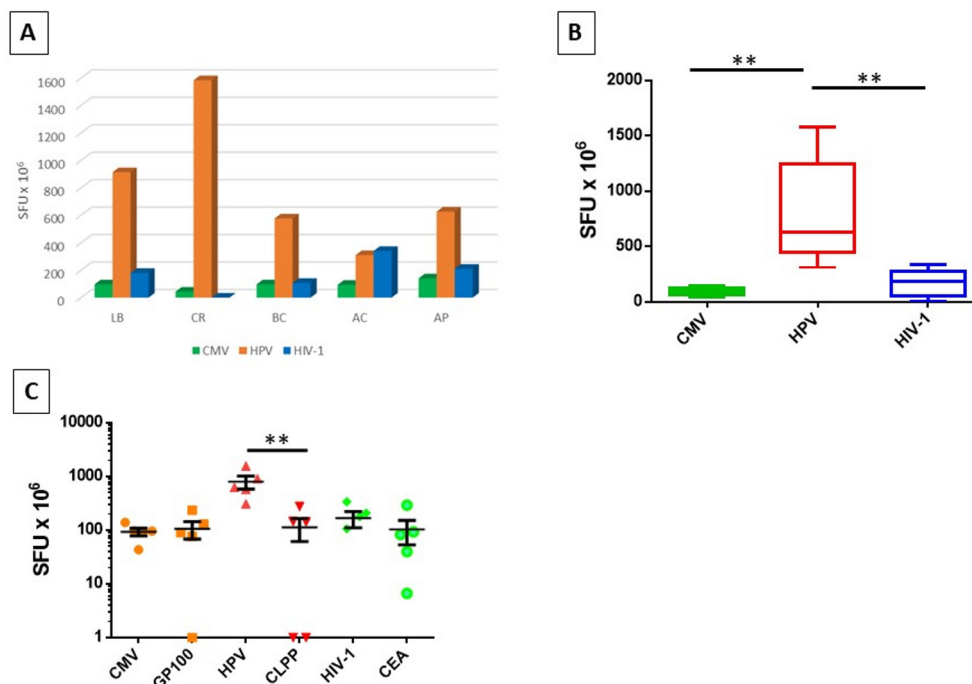


Figure 3 Ex vivo immunization with paired peptides. PBMCs from HLA-A*02:01 positive healthy subjects were immunized ex vivo with viral peptides. After 14 days, IFN γ EliSpot assay was performed restimulating the cells with the same viral peptide or with the paired tumor-associated antigen (TAA) peptide. Individual (A) and average (B) responsiveness to each viral peptide. (C) Average cross-reactivity versus viral and paired TAA peptides. SFU = IFN γ spot forming units.

Prediction of cross-reactive antitumor T cell response

Simulation experiments of cross-reactive antitumor T cells responses induced by the homologous viral epitopes were designed as previously described.⁴⁰

Each experiment simulated an in vivo vaccination with a TAA or its homologous viral epitope consisting of five injections at days 7, 10, 13, 16 and 19. A subsequent challenge was simulated with 1×10^3 cancer cells expressing the TAA. The simulations showed that in most cases the clearance of the tumor cells is reached within an identical timeframe and curve's shape, suggesting that the T cell immune response induced by the viral epitopes has the same antitumor efficacy as the one induced by the paired TAA. In other cases, for which the prediction affinity and stability values are significantly different, the timeframe is slightly (HSPH1), significantly (HEPACAM, TELOMERASE) delayed or no cross-reactivity is observed at all (KIF20A). Interestingly, the simulation model is able to assess the limited cross-reactivity between paired peptides with similar prediction affinity and stability values but showing a significant conformational difference (CLPP/HPV; MUC1/HHV8; SECERNIN1/INFLUENZA) (figure 4A,B). The same simulation approach is able to predict the role of the CD8⁺ T cell subset in the biological effect. Indeed, the curves of tumor growth show a rapid and steep increase when the removal at day 40 of the CD8⁺ T cells is simulated in the experimental models, and the percentage of cancer-free samples does not reach the zero (figure 4C,D).

DISCUSSION

In the present study we aimed at identifying, for the first time, viral epitopes with sequence and structural homology to TAAs, to be selected for eliciting an efficient cross-reacting CD8⁺ T cell response with a potential strong anticancer activity. Indeed, previous seminal studies by Oldstone have showed the same type of homology only between viral sequences and cellular antigens (the so called "molecular mimicry"), laying the foundation for the biological mechanisms driving the autoimmune diseases.^{43–45}

All the TAAs from the cancer peptide database have been analyzed and a list of nonamer peptides have been predicted as SBs to the MHC class-I HLA-A*01:01, 02:01, 03:01 and 24:02 alleles, which altogether cover about 50% of the world population. In particular, about 60% of the European as well as the north American Caucasian populations, 50% of the Japanese population, 30% of the Chinese population, 20% of the Indian population (<http://www.allelefreqencies.net>). Among the predicted SBs, only those with a very high affinity (<100 nM) have been selected, given that, according to our previous studies, only these are confirmed to bind the HLA-A*02:01 molecule in 100% of the cases.³⁷ Overall, 99 SBs have been predicted for the four alleles analyzed; 75.7% of them restricted to the HLA-A*02:01% and 54.6% of these belonging to the overexpressed subgroup. A large number (n=82) of viral sequences sharing homology with the TAAs were identified and the vast majority (n=75) were HLA-A*02:01 restricted. Such sequences were not

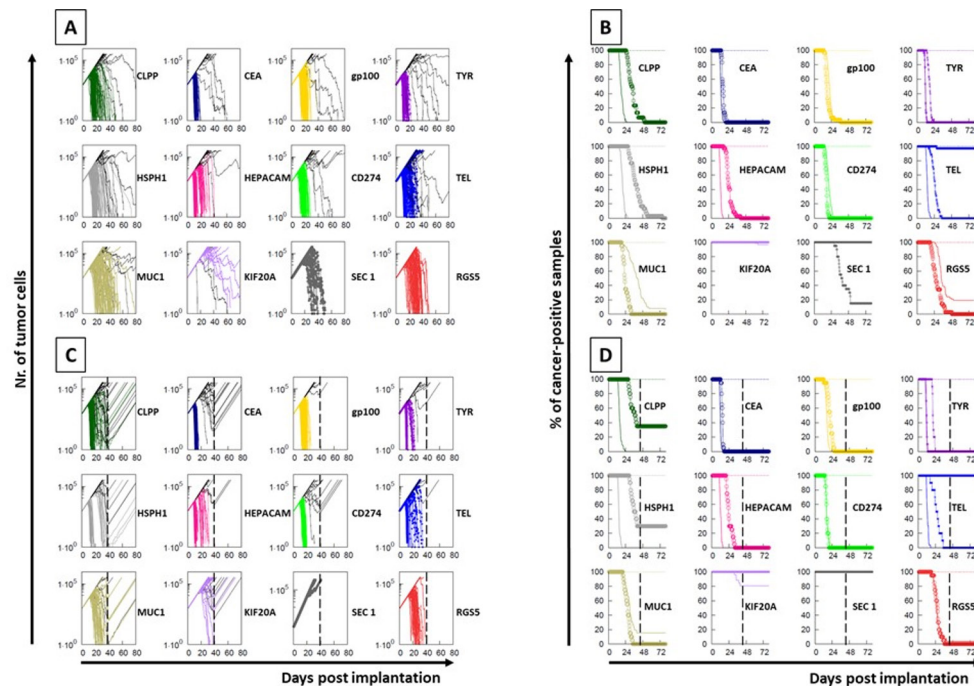


Figure 4 Simulation of immunization. An in vivo immunization and tumor challenge was simulated with 100 replicates. Multiple administrations of the viral or the paired TAA peptides were considered; the challenge was simulated with cancer cells expressing the tumor-associated antigen (TAA) peptide. The tumor growth (A) and the inverted Kaplan-Meier survival curve (B) are shown for each protocol. The same protocols were executed simulating the complete ablation of CD8⁺ T cells (C, D). In each paired peptides, the solid line indicates the results obtained with the TAA immunization while the circled line indicates the results obtained with the paired viral peptide immunization.

uniformly derived from different human viruses. Indeed, the HIV-1 contributed by far with the largest number of viral sequences (36/82), followed by the herpesviruses (22/82) and the outdistanced human papillomaviruses (9/82). However, only 20 of such viral sequences are predicted to be SBs to the corresponding MHC-class I alleles. Strikingly, 45% of these sequences are derived from Gag and Env HIV-1 proteins, which is unlike to be a random observation (online supplemental figure 5). On the contrary, this would indicate that HIV-1 provide a significant number of TAA-like epitopes, supporting the epidemiological notion that people living with HIV or AIDS (PLWHA) have a significantly lower incidence of non-viral associated solid tumors compared with the HIV-negative population.^{46 47} Of interest is also the observed homology between the melanoma-associated tyrosinase TAA and an epitope derived from the HERVK env protein. Indeed, the HERVK expression in melanoma has been reported and a cross-reacting T cell response may play a relevant role in tumor prognosis.⁴⁸

The epitope modeling showed that most of the paired TAA and viral epitopes not only share the same conformation but also the same contact patterns when docked into the HLA-A*02:01 molecule. In most cases, the paired peptides show the same contact patterns with the TCR α and β chains. The best examples are represented by the gp100/HCMV, the HEPACAM/ENCEPH, the CD274/HIV, tyrosinase/HIV, CEA/HIV and telomerase/HIVa pairs for which the contact pattern with the HLA-A*02:01

as well as the TCR α and β chains are identical. This would strongly suggest that, for each pair, the same CD8⁺ T cell clone may be able to cross-react with both peptides when presented in the context of the HLA-A*02:01 molecule. Moreover, in all cases, with the exception for the tyrosinase/HERV and CEA/HIVa pairs, the contact pattern with the TCR β chain is identical for paired epitopes suggesting that the reacting CD8⁺ T clones may express a TCR sharing the same β chain coupled with a different α chain. As anticipated, structural homologies between pair of peptides are highly dependent on the type of amino acid changes at specific positions and conservative changes are always predictive of structural preservation.

Furthermore, the number and the distance of hydrogen bonds formed by the residues of the paired epitopes with the HLA-A*02:01, the TCR α and β chains fully confirm the contact patterns as well as the predicted values of binding and stability. The lack of the homology between the analyzed peptides and the HTLV-1 Tax peptide crystallized in the 1AO7 structure may represent a bias for the constrained conformation. Nevertheless, regardless of the selected surrogate model, the different conformation and contact pattern between the peptide pairs evaluated in the present study confirm that indeed the approach is reliable to evaluate and compare conformation and molecular docking of peptides.

The biological confirmation of cross-reactive T cell responses against the paired peptides was assessed by ex



vivo immunization experiments. PBMCs were induced for 14 days with the viral epitope and restimulated in parallel with the vaccine viral peptide and the paired TAA peptide. The results clearly showed induction of a significant cross-reactive response within the paired peptides. This effect was directly correlated with the conformational homology between the paired peptides. Indeed, the lowest cross-reactivity was observed between the HPV and CLPP peptides characterized by a significant conformational difference due to the C to K amino acid mismatch at position 4. The immunological cross-reactivity induced by paired peptides was further confirmed using a simulation approach, showing a noteworthy concordance with the prediction values as well as the conformational similarities. Indeed, also in this approach, the simulation of a vaccination with the HPV peptide showed the induction of a partial cross-protection against tumor cells expressing the paired CLPP TAA, while vaccination with the CMV and HIV-1 peptides induced a perfectly matching protection against tumor cells expressing the paired gp100 and CEA TAAs, respectively.

In conclusion, the present study shows for the first time the high sequence and structural homology between TAAs and viral sequences. In some cases, such homologies are striking. The number of high homologous epitope pairs is unlike to be a random event, given that the probability of an identical stretch of seven or eight amino acid in a nonamer sequence is extremely low (7.8×10^{-10} and 3.9×10^{-11} , respectively).

On the contrary, this would strongly support the concept that TAAs and viral antigens may converge in the evolutionary process and may represent two sides of the same coin. In this respect, the previous exposure to specific viral epitopes may result in the establishment of a bi-specific antiviral/anticancer T cell memory if a cancer would develop during the lifetime presenting, by chance, a TAA sharing sequence and conformation similarities with the viral epitope. This may ultimately represent a relevant selective advantage for patients with cancer and may provide a totally new set of antigens for developing a novel preventive anticancer vaccine strategy.

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REFERENCES

- Melero I, Gaudernack G, Gerritsen W, *et al*. Therapeutic vaccines for cancer: an overview of clinical trials. *Nat Rev Clin Oncol* 2014;11:509–24.
- Pol J, Bloy N, Buqué A, *et al*. Trial Watch: peptide-based anticancer vaccines. *Oncoimmunology* 2015;4:e974411.
- Melief CJM, van Hall T, Arens R, *et al*. Therapeutic cancer vaccines. *J Clin Invest* 2015;125:3401–12.
- Tran T, Blanc C, Granier C, *et al*. Therapeutic cancer vaccine: building the future from lessons of the past. *Semin Immunopathol* 2019;41:69–85.
- Buonaguro FM, Tornesello ML, Buonaguro L. Virus-like particle vaccines and adjuvants: the HPV paradigm. *Expert Rev Vaccines* 2009;8:1379–98.
- Visciano ML, Diomedea L, Tagliamonte M, *et al*. Generation of HIV-1 virus-like particles expressing different HIV-1 glycoproteins. *Vaccine* 2011;29:4903–12.
- Buonaguro L, Tagliamonte M. Selecting target antigens for cancer vaccine development. *Vaccines* 2020;8. doi:10.3390/vaccines8040615. [Epub ahead of print: 17 Oct 2020].
- Vonderheide RH, Hahn WC, Schultze JL, *et al*. The telomerase catalytic subunit is a widely expressed tumor-associated antigen recognized by cytotoxic T lymphocytes. *Immunity* 1999;10:673–9.
- Disis ML, Wallace DR, Gooley TA, *et al*. Concurrent trastuzumab and HER2/neu-specific vaccination in patients with metastatic breast cancer. *J Clin Oncol* 2009;27:4685–92.
- Chang K, Pastan I. Molecular cloning of mesothelin, a differentiation antigen present on mesothelium, mesotheliomas, and ovarian cancers. *Proc Natl Acad Sci U S A* 1996;93:136–40.
- Finn OJ, Gantt KR, Lepisto AJ, *et al*. Importance of MUC1 and spontaneous mouse tumor models for understanding the immunobiology of human adenocarcinomas. *Immunol Res* 2011;50:261–8.
- Parkhurst MR, Fitzgerald EB, Southwood S, *et al*. Identification of a shared HLA-A*0201-restricted T-cell epitope from the melanoma antigen tyrosinase-related protein 2 (TRP2). *Cancer Res* 1998;58:4895–901.
- Correale P, Walmsley K, Nieroda C, *et al*. In vitro generation of human cytotoxic T lymphocytes specific for peptides derived from prostate-specific antigen. *J Natl Cancer Inst* 1997;89:293–300.
- Lam KW, Li CY, Yam LT, *et al*. Improved immunohistochemical detection of prostatic acid phosphatase by a monoclonal antibody. *Prostate* 1989;15:13–21.
- De Smet C, Lurquin C, van der Bruggen P, *et al*. Sequence and expression pattern of the human MAGE2 gene. *Immunogenetics* 1994;39:121–9.

- 16 Gnjatic S, Cao Y, Reichelt U, *et al.* NY-CO-58/KIF2C is overexpressed in a variety of solid tumors and induces frequent T cell responses in patients with colorectal cancer. *Int J Cancer* 2010;127:381–93.
- 17 Hofmann O, Caballero OL, Stevenson BJ, *et al.* Genome-wide analysis of cancer/testis gene expression. *Proc Natl Acad Sci U S A* 2008;105:20422–7.
- 18 Simpson AJG, Caballero OL, Jungbluth A, *et al.* Cancer/testis antigens, gametogenesis and cancer. *Nat Rev Cancer* 2005;5:615–25.
- 19 Karbach J, Neumann A, Atmaca A, *et al.* Efficient in vivo priming by vaccination with recombinant NY-ESO-1 protein and CpG in antigen naive prostate cancer patients. *Clin Cancer Res* 2011;17:861–70.
- 20 Theobald M, Biggs J, Hernández J, *et al.* Tolerance to p53 by A2.1-restricted cytotoxic T lymphocytes. *J Exp Med* 1997;185:833–42.
- 21 Buonaguro L, Tornesello ML, Gallo RC, *et al.* Th2 polarization in peripheral blood mononuclear cells from human immunodeficiency virus (HIV)-infected subjects, as activated by HIV virus-like particles. *J Virol* 2009;83:304–13.
- 22 Parmiani G, Castelli C, Dalerba P, *et al.* Cancer immunotherapy with peptide-based vaccines: what have we achieved? Where are we going? *J Natl Cancer Inst* 2002;94:805–18.
- 23 Fikes JD, Sette A. Design of multi-epitope, analogue-based cancer vaccines. *Expert Opin Biol Ther* 2003;3:985–93.
- 24 Carrabba MG, Castelli C, Maeurer MJ, *et al.* Suboptimal activation of CD8(+) T cells by melanoma-derived altered peptide ligands: role of Melan-A/MART-1 optimized analogues. *Cancer Res* 2003;63:1560–7.
- 25 Parkhurst MR, Salgaller ML, Southwood S, *et al.* Improved induction of melanoma-reactive CTL with peptides from the melanoma antigen gp100 modified at HLA-A*0201-binding residues. *J Immunol* 1996;157:2539–48.
- 26 Chen JL, Dunbar PR, Gileadi U, *et al.* Identification of NY-ESO-1 peptide analogues capable of improved stimulation of tumor-reactive CTL. *J Immunol* 2000;165:948–55.
- 27 Dao T, Korontsvit T, Zakhaleva V, *et al.* An immunogenic WT1-derived peptide that induces T cell response in the context of HLA-A*02:01 and HLA-A*24:02 molecules. *Oncoimmunology* 2017;6:e1252895.
- 28 Bae J, Samur M, Munshi A, *et al.* Heteroclitic XBP1 peptides evoke tumor-specific memory cytotoxic T lymphocytes against breast cancer, colon cancer, and pancreatic cancer cells. *Oncoimmunology* 2014;3:e970914.
- 29 Birnbaum ME, Mendoza JL, Sethi DK, *et al.* Deconstructing the peptide-MHC specificity of T cell recognition. *Cell* 2014;157:1073–87.
- 30 Stone JD, Chervin AS, Kranz DM. T-cell receptor binding affinities and kinetics: impact on T-cell activity and specificity. *Immunology* 2009;126:165–76.
- 31 Hawse WF, De S, Greenwood AI, *et al.* TCR scanning of peptide/MHC through complementary matching of receptor and ligand molecular flexibility. *J Immunol* 2014;192:2885–91.
- 32 Balachandran VP, Łuksza M, Zhao JN, *et al.* Identification of unique neoantigen qualities in long-term survivors of pancreatic cancer. *Nature* 2017;551:512–6.
- 33 Tornesello ML, Buonaguro L, Izzo F, *et al.* Molecular alterations in hepatocellular carcinoma associated with hepatitis B and hepatitis C infections. *Oncotarget* 2016;7:25087–102.
- 34 Snyder A, Makarov V, Merghoub T, *et al.* Genetic basis for clinical response to CTLA-4 blockade in melanoma. *N Engl J Med* 2014;371:2189–99.
- 35 Rizvi NA, Hellmann MD, Snyder A, *et al.* Cancer immunology. Mutational landscape determines sensitivity to PD-1 blockade in non-small cell lung cancer. *Science* 2015;348:124–8.
- 36 Buonaguro L, Cerullo V. Pathogens: our allies against cancer? *Mol Ther* 2021;29:10–12.
- 37 Petruzzo A, Tagliamonte M, Mauriello A, *et al.* Unique true predicted neoantigens (TPNAs) correlates with anti-tumor immune control in HCC patients. *J Transl Med* 2018;16:286.
- 38 Reynisson B, Alvarez B, Paul S, *et al.* NetMHCpan-4.1 and NetMHCIIpan-4.0: improved predictions of MHC antigen presentation by concurrent motif deconvolution and integration of MS MHC eluted ligand data. *Nucleic Acids Res* 2020;48:W449–54.
- 39 Rasmussen M, Fenoy E, Harndahl M, *et al.* Pan-Specific prediction of peptide-MHC class I complex stability, a correlate of T cell immunogenicity. *J Immunol* 2016;197:1517–24.
- 40 Rapin N, Lund O, Bernaschi M, *et al.* Computational immunology meets bioinformatics: the use of prediction tools for molecular binding in the simulation of the immune system. *PLoS One* 2010;5:e9862.
- 41 Miyazawa S, Jernigan RL. Residue-residue potentials with a favorable contact pair term and an unfavorable high packing density term, for simulation and threading. *J Mol Biol* 1996;256:623–44.
- 42 von Eichborn J, Woelke AL, Castiglione F, *et al.* Vacclmm: simulating peptide vaccination in cancer therapy. *BMC Bioinformatics* 2013;14:127.
- 43 Fujinami RS, Oldstone MB, Wroblewska Z, *et al.* Molecular mimicry in virus infection: crossreaction of measles virus phosphoprotein or of herpes simplex virus protein with human intermediate filaments. *Proc Natl Acad Sci U S A* 1983;80:2346–50.
- 44 Fujinami RS, Oldstone MB. Amino acid homology between the encephalitogenic site of myelin basic protein and virus: mechanism for autoimmunity. *Science* 1985;230:1043–5.
- 45 Oldstone MB. Molecular mimicry and autoimmune disease. *Cell* 1987;50:819–20.
- 46 Grulich AE, Vajdic CM. The epidemiology of cancers in human immunodeficiency virus infection and after organ transplantation. *Semin Oncol* 2015;42:247–57.
- 47 Calabresi A, Ferraresi A, Festa A, *et al.* Incidence of AIDS-defining cancers and virus-related and non-virus-related non-AIDS-defining cancers among HIV-infected patients compared with the general population in a large health district of Northern Italy, 1999–2009. *HIV Med* 2013;14:481–90.
- 48 Schmitt K, Reichrath J, Roesch A, *et al.* Transcriptional profiling of human endogenous retrovirus group HERV-K(HML-2) loci in melanoma. *Genome Biol Evol* 2013;5:307–28.