



Impact of Structural Observables From Simulations to Predict the Effect of Single-Point Mutations in MHC Class II Peptide Binders

Rodrigo Ochoa^{1,2}, Roman A. Laskowski², Janet M. Thornton² and Pilar Cossio^{1,3*}

¹Biophysics of Tropical Diseases, Max Planck Tandem Group, University of Antioquia UdeA, Medellín, Colombia, ²European Molecular Biology Laboratory, European Bioinformatics Institute (EMBL-EBI), Cambridge, United Kingdom, ³Department of Theoretical Biophysics, Max Planck Institute of Biophysics, Frankfurt am Main, Germany

OPEN ACCESS

Edited by:

Gregory Bowman,
Washington University School of
Medicine in St. Louis, United States

Reviewed by:

Carlo Camilloni,
University of Milan, Italy
Sophie Sacquin-Mora,
UPR9080 Laboratoire de Biochimie
Théorique, France

*Correspondence:

Pilar Cossio
pilar.cossio@biophys.mpg.de

Specialty section:

This article was submitted to
Biological Modeling and Simulation,
a section of the journal
Frontiers in Molecular Biosciences

Received: 01 December 2020

Accepted: 15 February 2021

Published: 30 March 2021

Citation:

Ochoa R, Laskowski RA, Thornton JM
and Cossio P (2021) Impact of
Structural Observables From
Simulations to Predict the Effect of
Single-Point Mutations in MHC Class II
Peptide Binders.
Front. Mol. Biosci. 8:636562.
doi: 10.3389/fmolb.2021.636562

The prediction of peptide binders to Major Histocompatibility Complex (MHC) class II receptors is of great interest to study autoimmune diseases and for vaccine development. Most approaches predict the affinities using sequence-based models trained on experimental data and multiple alignments from known peptide substrates. However, detecting activity differences caused by single-point mutations is a challenging task. In this work, we used interactions calculated from simulations to build scoring matrices for quickly estimating binding differences by single-point mutations. We modelled a set of 837 peptides bound to an MHC class II allele, and optimized the sampling of the conformations using the Rosetta backrub method by comparing the results to molecular dynamics simulations. From the dynamic trajectories of each complex, we averaged and compared structural observables for each amino acid at each position of the 9^{mer} peptide core region. With this information, we generated the scoring-matrices to predict the sign of the binding differences. We then compared the performance of the best scoring-matrix to different computational methodologies that range in computational costs. Overall, the prediction of the activity differences caused by single mutated peptides was lower than 60% for all the methods. However, the developed scoring-matrix in combination with existing methods reports an increase in the performance, up to 86% with a scoring method that uses molecular dynamics.

Keywords: MHC class II, single-point mutation, structural bioinformatics, simulations, binding

INTRODUCTION

The Major Histocompatibility Complex (MHC) class II is a key receptor responsible for recognizing fragments of proteins belonging to external pathogens, as well as recognizing human proteins that can boost the emergence of autoimmune events and immunological processes (Wieczorek et al., 2017). The structures of multiple MHC class II alleles have been elucidated. They are composed of α and β chains split into four sub-units, two of them forming a groove where the peptides bind (Bjorkman, 2015) (see **Supplementary Figure S1**). The peptides contain a core region, which is a fragment of nine amino acids responsible to stabilize the peptide-MHC class II interaction. The peptide-core binds in four key pockets of the receptor that are formed between the α and β chains (Unanue et al., 2016). The available structures of MHC class II bound to peptides provide

information about the binding poses, which are commonly in a polyproline II-like extended conformation (Bermúdez et al., 2014). Understanding the preference of amino acids for certain positions is relevant to comprehending how epitopes can trigger adaptive immune responses (Unanue et al., 2016). Moreover, this structural information allows us to study the physicochemical interactions within key pockets in the binding groove, which is crucial to stabilizing the complexes (Yeturu et al., 2010).

These structural insights are usually not included in the prediction tools of peptides binding to the MHC class II. The lack of structural and dynamical representations of the complexes, as well as the demand on computational resources, are some of the limitations (Zhang et al., 2010). Instead, researchers have focused on generating profiles and motifs of sequences using information from bioactivity datasets (Wang et al., 2008). The main purpose of these tools is to rank peptide-binders by their predicted affinities, and associate the values to a potential immunological response. Among the available approaches, the most common ones are machine learning models trained with a diverse set of peptides bound to different MHC class II alleles (Andreatta et al., 2015; Peters et al., 2020). Some other researchers have focused on creating position-specific scoring matrices that can be implemented to select peptide candidates through simple bioinformatics pipelines, and to predict which core region of the peptide is responsible for the interaction with the main pockets of the receptor (Rapin et al., 2008). The available tools cover a diverse set of MHC class II alleles, providing clues for researchers working on the design of vaccines and immunotherapies (Nandy and Basak, 2016).

One particular challenge about the binding predictions is to evaluate affinity differences for single-point mutations on the peptide. Efforts have been focused to understand the impact of such mutations in the context of protein function, participation in molecular pathways and changes in their physico-chemical properties (Bogan and Thorn, 1998; Tokuriki et al., 2007; Hopf et al., 2017). From a structural perspective, coordinates can be used as input to predict the side chain conformations of the mutated amino acids, and assess their impact from a stability or binding perspective (Li et al., 2014). In the case of MHC class II, sequence-based strategies can be implemented to predict these activity differences, but structural and dynamical insights about the mechanisms behind these modifications are also relevant (Kuhlman and Bradley, 2019; Aranha et al., 2020). Many of these methods rely on energy evaluations to check differences in terms of solvent exposure, generation of hydrogen bonds, electrostatics contributions, backbone and side chain flexibility, and weak interactions such as van der Waals (Sammond et al., 2007; Slutzki et al., 2015; Barlow et al., 2018). Understanding the main drivers of these affinity differences is relevant for the design and discovery of novel peptide binders.

Methods using structural and dynamical information can be implemented to assess the role of the peptide/receptor conformations in the binding affinity and stability (Antunes et al., 2018; Lanzarotti et al., 2018). For MHC class II, the crystal structures show that peptides tend to bind in similar

conformations for the available alleles (Wieczorek et al., 2016). Therefore, these structures can be used as templates to model other peptides bound to the receptor, and enable the study of how modifications can affect the binding from a physicochemical perspective (Ochoa et al., 2019). These models can be subjected to conformational sampling to analyze the fluctuations of the complexes in equilibrium (Ferrante et al., 2015) and score the most favourable conformations (Cossio et al., 2012; Sarti et al., 2013).

Among the sampling approaches, molecular dynamics (MD) has proved to be a useful way of studying the conformational space of peptides bound to MHC class II structures (Omasits et al., 2008; Ochoa et al., 2019). However, the scalability is limited by the required computational resources if large sets of peptides are analyzed. One option is to implement Monte Carlo algorithms to obtain representative structures of the complexes in equilibrium (King and Bradley, 2010). This is the case of the backrub method from Rosetta, where the backbone flexibility is modelled based on observations from high-resolution crystal structures (Smith and Kortemme, 2008). The movements are mainly backbone rotations around the axes of C_{α} atoms that are accepted using a Metropolis criterion based on the minimization of a bond-angle penalty imposed by the chosen force fields (Smith and Kortemme, 2010). The trajectories provide information on the system's intrinsic flexibility, solvent accessibility and the main interactions (e.g., hydrogen bonds, non-bonded contacts) formed by the amino acids.

In this work, we evaluated how two kinds of molecular interactions can aid in the prediction of the affinity-differences for single modifications in the core region of a set of MHC class II peptide binders. For this purpose, we created a set of scoring matrices, as is typically done using sequence analysis, but here derived from structural observables from simulations of a large set of peptides/MHC class II complexes. The matrices allow the estimation of binding differences caused by single-point mutations, and complement current state-of-the-art methods to improve the predictions. We modelled a large set of peptides with binding data available for one representative MHC class II allele. Then, we sampled the conformational space using the backrub method optimized to reproduce the finite-temperature ensemble from molecular dynamics simulations. Hydrogen bonds and contact interactions were used to calculate the scoring-matrices SM-HB and SM-C, respectively, from the structural descriptors per core position in the peptide. The magnitude and stability of these observables were associated to binding differences of single-modified peptides.

In addition, five other approaches, having a wide range of computational costs, as well as accuracy, were assessed to predict the binding differences. Specifically, two sequence-based methods were implemented, which involve the use of a motif matrix to predict the most probable amino acids of the peptide core regions, and a machine learning tool used to predict binding affinities for this system. The third and fourth methods are a previously benchmarked structural/dynamical approach using an MD/scoring and backrub/scoring combination to rank peptides bound to the MHC class II (Ochoa et al., 2019). Finally, a

Molecular Mechanics-Poisson Boltzmann Surface Area (MM-PBSA) approach is used to calculate average energies per peptide based on the MD trajectories obtained in the previous strategy. In general, the predictions had an accuracy below 60% for all the methods, but combining the best scoring-matrix SM-HB (i.e., the one generated from the hydrogen bonds) with the existing methods improves the performance.

MATERIALS AND METHODS

In the following, we first explain how we build the scoring-matrices based on the structural observables. Then, we describe how to evaluate their impact on activity differences caused by single-point mutations on the peptide binders. This is followed by a description of the additional methods used for comparison and their combination with the developed structural scoring-matrices.

Structural Scoring-Matrices From Simulations

To evaluate the impact of structural interactions, we created a set of scoring matrices based on hydrogen bonds (SM-HB) and contacts (SM-C) generated between the peptide core region and residues of the MHC class II binding site. For that purpose, we first optimized the conformational sampling of MHC class II structures using the Rosetta backrub method (Davis et al., 2006) in comparison to MD simulations. Then, we modelled a large dataset of known peptide binders of the same MHC class II allele, and with the observables we generated the scoring matrices. A detailed explanation is presented below.

Conformational Sampling Optimization

Before checking the role of the structural interactions, we assessed the conformational sampling of the Monte Carlo backrub method in Rosetta in comparison to MD simulations to explore conformations of crystal structures of peptides bound to MHC class II alleles. We selected a set of 10 peptide-MHC class II crystal structures from the Protein Data Bank (PDB) (Berman et al., 2000) of the most widely studied allele, DRB1*01:01 (see Supplementary Text for details about the structure selection). We used this benchmark to compare molecular dynamics (MD) and Monte Carlo backrub simulations.

Molecular dynamics: Each crystal structure was subjected to MD simulations of 20 nanoseconds (ns) with previous minimization and NVT/NPT equilibration phases, using GROMACS v5.1 (Hess et al., 2008). The main MD parameters are described in the Supplementary Text. A temperature of 350 K was chosen to perform the simulations, allowing a fast exploration of the conformational space. Since we are interested only in the peptide-receptor interactions, all the protein atoms located at a distance greater than 12 Å from any peptide atom were restrained.

Backrub Monte Carlo: The same crystal structures were subjected to Metropolis Monte Carlo simulations using the backrub algorithm (Davis et al., 2006) available in

RosettaCommons version 2016.32 (www.rosettacommons.org). A total of 50,000 Monte Carlo trials were run per complex using two kT values: 0.35 and 1.2. C_α atoms were chosen as pivots for all the protein and peptide residues. The minimum backrub segment size in atoms was 3, and the maximum segment was 64. The probabilities for sampling side chain and backbone torsions were set at the default values. The simulations were run over a single core for each complex. An optimal backrub parameter setup was selected in order to reproduce the equilibrium ensemble from MD.

Structural observables

Several structural observables were used to characterize the conformations from the different simulations:

Side chain dihedrals: The side chain dihedrals χ_1 and χ_2 were monitored for all the amino acids belonging to the peptide, and the distributions were compared to that obtained from MD. The Kullback-Leibler divergence metric (Hershey and Olsen, 2007) was implemented to compare the distributions.

Main chain hydrogen bonds: We monitored interactions made by the amino acids of the peptide core region with the receptor. Specifically, we calculated the number of potential hydrogen bonds made by the backbone atoms using the HBPLUS program (McDonald and Thornton, 1994).

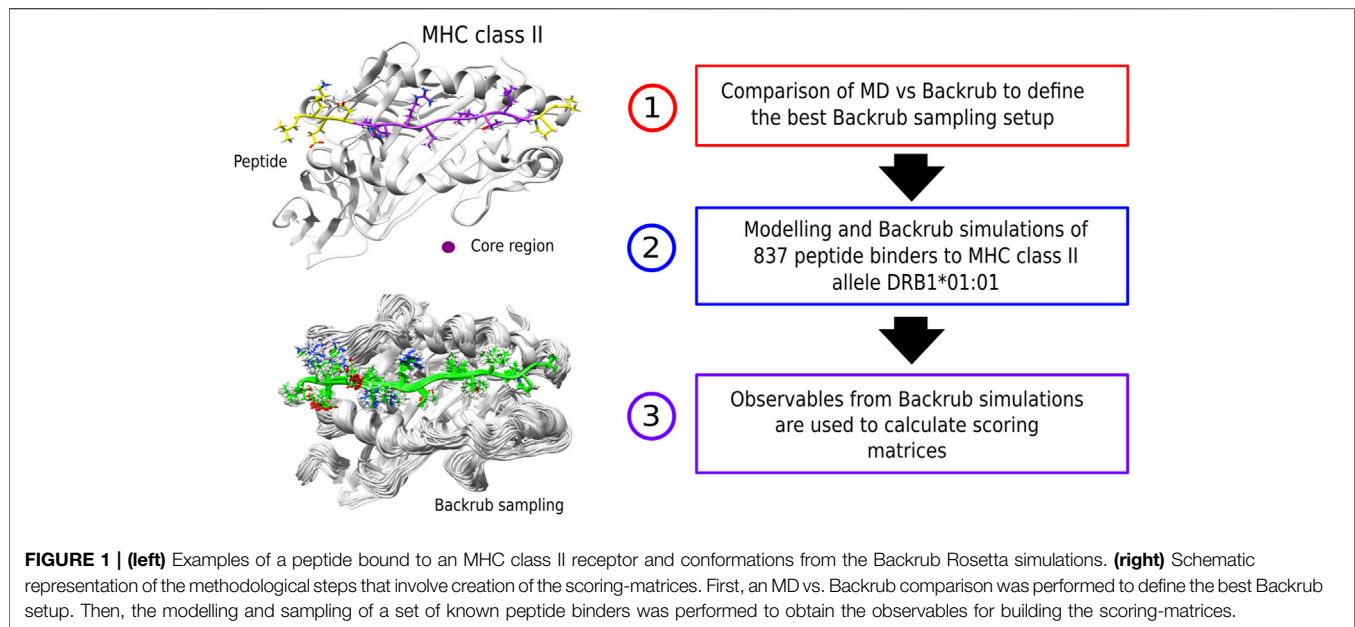
Contacts: We also calculated the number of non-bonded contacts with a threshold of 4 Å between the atoms of the peptide and those of the receptor using Biopython modules (Cock et al., 2009).

The latter two observables were also used to calculate the structural descriptors for creating the scoring-matrices.

Modelling and Simulations of a Large Dataset of Peptides Bound to MHC Class II

After establishing the best backrub simulation setup, a set of peptides with available binding data for different MHC class II alleles was modelled and simulated to calculate scoring-matrices from the chosen structural descriptors.

First, we selected as a representative structure of the allele DRB1*01:01 and the crystal structure with PDB id 1T5X, which is co-crystallized with a peptide that we used as template to model peptide binders with bioactivity information available. For the peptides, we used a public dataset containing 44,541 measured affinities covering 26 MHC class II alleles (Wang et al., 2010). We selected a total of 837 15 mer peptides for the allele DRB1*01:01 after applying the filter below, with activities from 1 to 10,000 nM. The filter was the prediction of the 9 mer core region of each selected peptide using two methods. The first was based on available motifs derived from a position-specific scoring matrix published for several MHC class II alleles (Rapin et al., 2008). The sequences were analyzed over windows of nine amino acids, where each fragment was scored to obtain a ranked list of fragments with probabilities of being the core region of the peptide interacting with the MHC class II receptor. For the second method, we implemented the NetMHCIIpan-4.0 tool, which has as its main goal the prediction of affinities for peptides bound to MHC class II molecules, and also the prediction of the 9^omer core regions of the peptide sequences (Andreatta et al.,



2015). A peptide was selected when both methods predicted identical core regions with the highest scores. As a final step, we aligned the predicted core region with the core from the peptide template. If, after the alignment, we needed to add more than two amino acids for either flanking region (N or C-terminal), the peptide was discarded.

We modelled the selected peptides by iterative single substitutions of the peptide template sequence. The mutations were performed with the package *fixbb* from Rosetta (Loffler et al., 2017), which was compared in a previous study to other available mutation protocols (Ochoa et al., 2018). The method selects the most probable rotamer from a dictionary of backbone-dependent conformations. After each mutation, the side chain atoms were relaxed with the backbone fixed. The modelling of additional amino acids in the flanking region, when required, was done with the *Remodel* package from RosettaCommons (Huang et al., 2011), where the new amino acid was subjected to the prediction of the rotamer with relaxation of the side chains.

For each peptide, the backrub simulation from Rosetta was applied with $kT = 1.2$ (Smith and Kortemme, 2008) as found to be optimal (see the Results). Each Monte Carlo simulation had 200,000 trials. We obtained 2,000 frames per simulation, and the previously described interactions (see Methods *Structural observables*) were calculated per amino acid in all the core positions for each frame. We did the same under three other scenarios: (i) using the last 1,000, (ii) using the 1,000 frames with best energy-scores [i.e., backrub scoring function (Alford et al., 2017)], and (iii) using the single frame with the lowest energy. A summary of the modelling and sampling strategies is shown on **Figure 1**.

Definition of the Scoring-Matrices

We calculated averages of the observables per amino acid in each position of the core to define scoring-matrices of the structural descriptors. The averages covered the number of amino acids

available in the dataset per position in the core region. For each position in the core region, we calculated a vector with 20 indices (one per each natural amino acid) using the average of the observable from the backrub trajectory. At the i th core position for amino acid type j , the average observable \mathcal{O} is defined as

$$\mathcal{O}_{ij} = \frac{1}{N_f} \sum_{\alpha} \sum_f o_{ij}^{\alpha f}, \quad (1)$$

where o is the observable, f is the frame number, N_f is the total number of frames and α indexes the simulation run (having one simulation for each binding-peptide from the dataset). In the case of using just one frame from the backrub trajectory, only the average across the simulation is calculated. If an amino acid type is not found at a given position for a certain run, the observable is taken as zero. We note that the amino acid distribution is not homogeneous but it is given by the natural-occurring frequencies found in the dataset. These intrinsic frequencies are implicitly taken into account in **Eq. 1**. This allows us to improve the available motifs of peptides binding to MHC class II alleles by adding weights due to the structural observables.

The Scoring-Matrix for a Given Observable is Defined as

$$E_{ij} = -\ln \frac{\mathcal{O}_{ij}}{\sum_j \mathcal{O}_{ij}} \quad (2)$$

which provides a scoring-energy for each amino acid (j) in each core position (i).

To visualize the frequency contribution of each amino acid on the peptide library and the scoring-matrices, logoplots were generated using the WebLogo3 server (Crooks et al., 2004).

Assessment of Single-point Mutation Activity Predictions

The obtained scoring-matrices, SM-HB and SM-C, were compared to other methods based on their capability to predict single-point mutation activity differences. The test consisted of predicting the sign of the experimental $\Delta\Delta G$ for each pair of peptides differing by single-point mutations in the peptide core region. A total of 112 peptides forming 56 pairs were selected and not used to calculate the scoring-matrices from the descriptors. One requirement to select the pairs of peptides is the prediction of identical core regions with high reliability, based on the same criteria used to model the peptides (see *Modelling and simulations of a large dataset of peptides bound to MHC class II*).

Additional Methodologies for Comparison

Five additional methods were used to compare and complement the results with the scoring-matrices. These methods are:

A sequence motif reported for allele DRB1*01:01 was used to compare the probabilities of finding an amino acid in the core region (Rapin et al., 2008). The higher the value in the matrix indicates a higher probability. The difference in probabilities was used to compare the differences in affinity.

The tool NetMHCIIpan was used to predict a numerical affinity per peptide. The sign of the predicted difference is compared to the sign of the experimental values for assessing the performance.

A hybrid MD/scoring approach was also used to predict the sign of the activity difference using structural models of the peptides based on a previously published protocol (Ochoa et al., 2019). In summary, each peptide was subjected to MD simulations of 10 ns using the same MD setup as explained previously. Each frame of the last half of the trajectory was scored using six different scoring functions: Haddock (Dominguez et al., 2003), Vina (Trott and Olson, 2009), a combination of DFIRE and GOAP (DFIRE-GOAP) (Yang and Zhou, 2008; Zhou and Skolnick, 2011), Pisa (Krissinel and Henrick, 2007), FireDock (Andrusier et al., 2007), and the BMF-BLUUES scoring combination (Berrera et al., 2003; Fogolari et al., 2012). If three or more scoring functions predicted the sign of the score differences equal to the sign of the experimental activity differences, it was counted as a match to assess the performance.

A hybrid backrub/scoring approach as explained in the previous strategy, using 50,000 Monte Carlo trials per run with a kT of 1.2. The backrub trajectory was scored using the same scoring functions and consensus criterion to match the sign of the activity difference.

Finally, as the most exhaustive approach, we calculated average energies per peptide complex using the MM-PBSA methodology. For that purpose we used the `g_mmpbsa` plugin (Kumari et al., 2014) to calculate the solvated and non-solvated terms using as input the MD trajectories of 10 ns calculated in the third strategy.

Combination With the Structural Scoring-Matrices

To improve the performances, we combined the previous approaches with the scoring-matrices results. Specifically, we evaluated if using the scoring-matrices together with other

TABLE 1 | Percentage of amino acids per backrub configuration ($kT = 0.35$ and $kT = 1.2$) for each side chain dihedral that sampled the conformational space similarly to MD simulations among all the 10 MHC class II crystal structures

Side chain dihedrals	$kT = 0.35$ (%)	$kT = 1.2$ (%)
χ_1	19.2	80.8
χ_2	12.9	87.1

methods can increase the number of predictions after checking by pairs if either of the two methods predicts correctly the sign of the mutation activity difference. This analysis works as a conditional “or” to evaluate how many cases can be covered using more than one method, and subsequently observe how many predictions match the experimental data.

RESULTS

To evaluate the impact of interactions in affinity changes caused by single-point mutations in MHC class II peptide binders, a set of scoring-matrices was calculated to assign probabilities for each type of amino acid in each position of the peptide core region. The matrices are created using the main chain hydrogen bonds (SM-HB), and the non-bonded contacts (SM-C) obtained from trajectories of peptides in complex with the MHC class II allele. To optimize the sampling, we first compared the Backrub approach to the results from MD simulations, in order to guarantee enough conformational exploration with computationally efficiency.

Optimization of the Structural Scoring-Matrices

Backrub Simulation Optimization

We optimized the kT parameter used in backrub Rosetta simulations in comparison to finite temperature MD simulations. We used as benchmark a set of 10 peptide-MHC class II structures of allele DRB1*01:01, available in the PDB (see Supplementary Text, **Supplementary Table S1**; **Supplementary Figure S2**). After subjecting the crystal complexes to both sampling methods, the trajectories were analyzed based on several structural observables for different kT . First, we calculated the distributions of the χ_1 and χ_2 for each amino acid of the peptide. Examples comparing the results of MD to backrub sampling using $kT = 0.35$ and $kT = 1.2$ are shown in **Figure 2** for two amino acids. **Supplementary Table S1** shows how many amino acids were sampled similarly between the backrub and MD configurations using the side chain-dihedral distributions (see Supplementary Text and **Supplementary Figure S3** for details and additional validations). We find that using the backrub simulations with $kT = 1.2$ is suitable to efficiently explore the side chain dihedrals in comparison to MD.

We then calculated the average of the number contacts and the number of hydrogen bonds created by the main chain atoms (**Table 2**) for the amino acids located in the core region and for both sampling methodologies (using the optimal kT for backrub Rosetta). The fractional error calculated using standard deviation

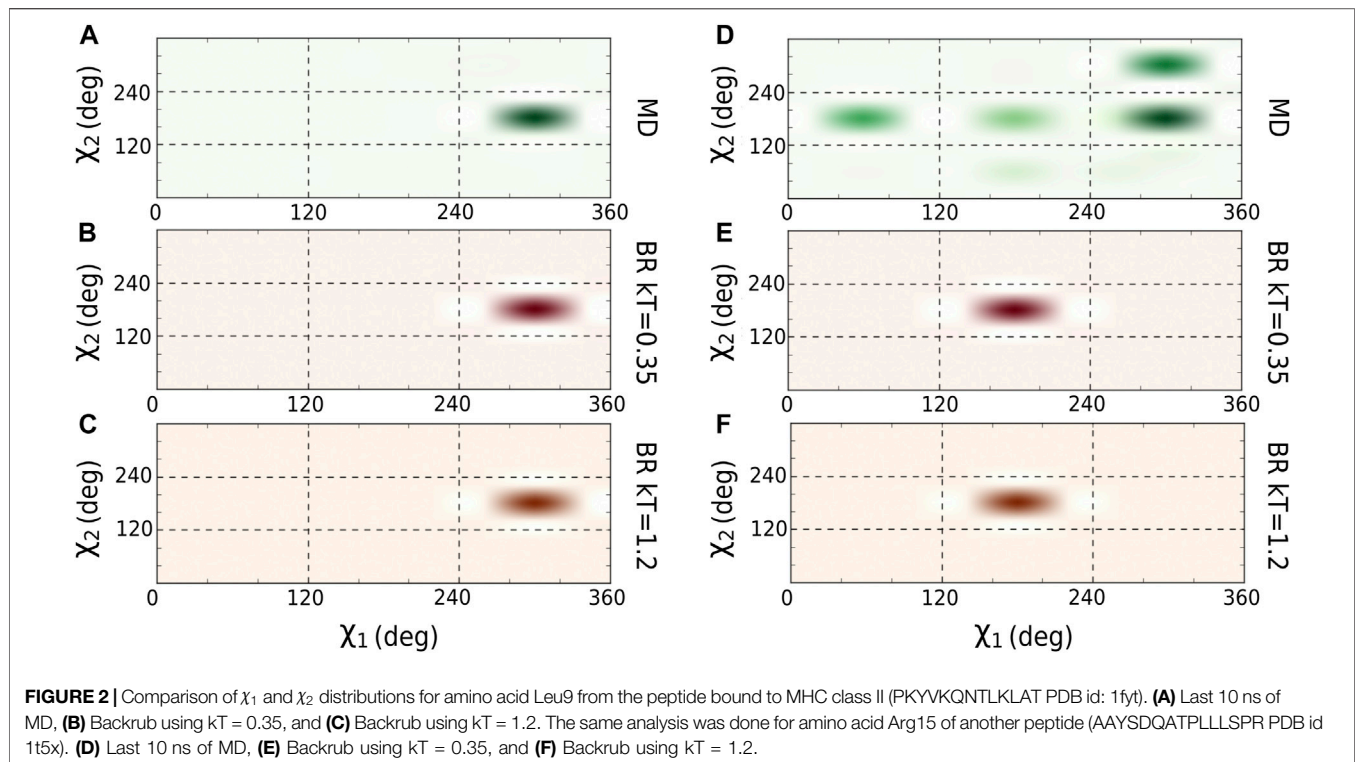


TABLE 2 | Average and fractional error of the number of contacts and hydrogen bonds (HB) made by the main chain atoms of the peptide-core amino acids bound to MHC class II, and sampled with MD or backrub (BR) using $kT = 1.2$. The fractional error was calculated using the standard deviation from the simulations for each peptide core position. The last row shows an average value for all the structures.

PDB	MD contacts	BR contacts	MD HB	BR HB
1ft	147.9 ± 12.5	148.1 ± 9.8	8.7 ± 1.1	7.4 ± 1.1
1klg	112.6 ± 9.9	104.0 ± 7.8	8.5 ± 1.1	8.3 ± 1.2
1sje	130.3 ± 10.5	104.5 ± 7.3	10.5 ± 0.9	8.6 ± 1.1
1sjh	115.1 ± 10.6	107.8 ± 9.9	8.4 ± 1.1	9.9 ± 1.0
1t5x	135.4 ± 11.8	72.5 ± 10.1	7.8 ± 1.0	3.7 ± 1.0
2fse	126.1 ± 13.0	96.8 ± 8.9	8.9 ± 1.1	6.4 ± 0.8
3pgd	129.9 ± 13.5	133.3 ± 9.4	9.2 ± 1.1	8.7 ± 0.7
4aen	114.6 ± 11.3	99.0 ± 7.6	8.2 ± 1.2	7.4 ± 1.1
4i5b	134.8 ± 10.8	126.5 ± 9.6	8.9 ± 1.2	8.1 ± 1.1
4ov5	161.1 ± 13.8	133.9 ± 11.0	10.2 ± 1.2	8.5 ± 0.7
Average	130.7 ± 11.8	112.6 ± 9.2	8.9 ± 1.1	7.7 ± 1.0

of the simulations is also shown in **Table 2**. We find that the averages for the backrub method are slightly lower than those for MD but within error estimates. Correlations of the values are shown in **Supplementary Figure S4**. The impact of the selected structural descriptors will be discussed in later sections.

Scoring-Matrices From Optimized Backrub Simulations

We selected a total of 837 15-mer peptides from the chosen bioactivity dataset (Nielsen et al., 2010) after filtering, as described in the Methods. The peptides were simulated with backrub using

$kT = 1.2$. The number of hydrogen bonds made by the main chain, and number of non-bonded contacts were calculated from the structure in the trajectories. These observables were averaged and used to calculate the scoring-matrices SM-HB and SM-C per amino acid in the core region according to the equations in the Methods.

These scoring-matrices incorporate the frequency of the structural descriptors obtained from all the sampled peptides, as well as the amino acid distribution of the peptide library. In **Figure 3**, we show the frequency of the amino acid distribution in the set of 837 peptides (**Figure 3A**) and the motif of the peptide core region obtained from the SM-HB as observable (**Figure 3B**). The motif for the SM-C is available in the **Supplementary Figure S5**.

Assessment of the Scoring-Matrices to Predict MHC II- Peptide Activity Differences

We first assessed if the scoring-matrices are able to predict correctly the sign of activity differences by single-point mutations on the peptide core region. The 56 pairs of peptides differing in single amino acids are reported in the **Supplementary Table S2** with the corresponding experimental activities per peptide, and the difference values. This information was obtained from the bioactivity dataset (Wang et al., 2010), which follows experimental gold-standard protocols for binding measurements to MHC receptors, in comparison to other techniques (Kastritis and Bonvin, 2010). We note that this set of peptides was not included during the creation of the scoring-matrices.

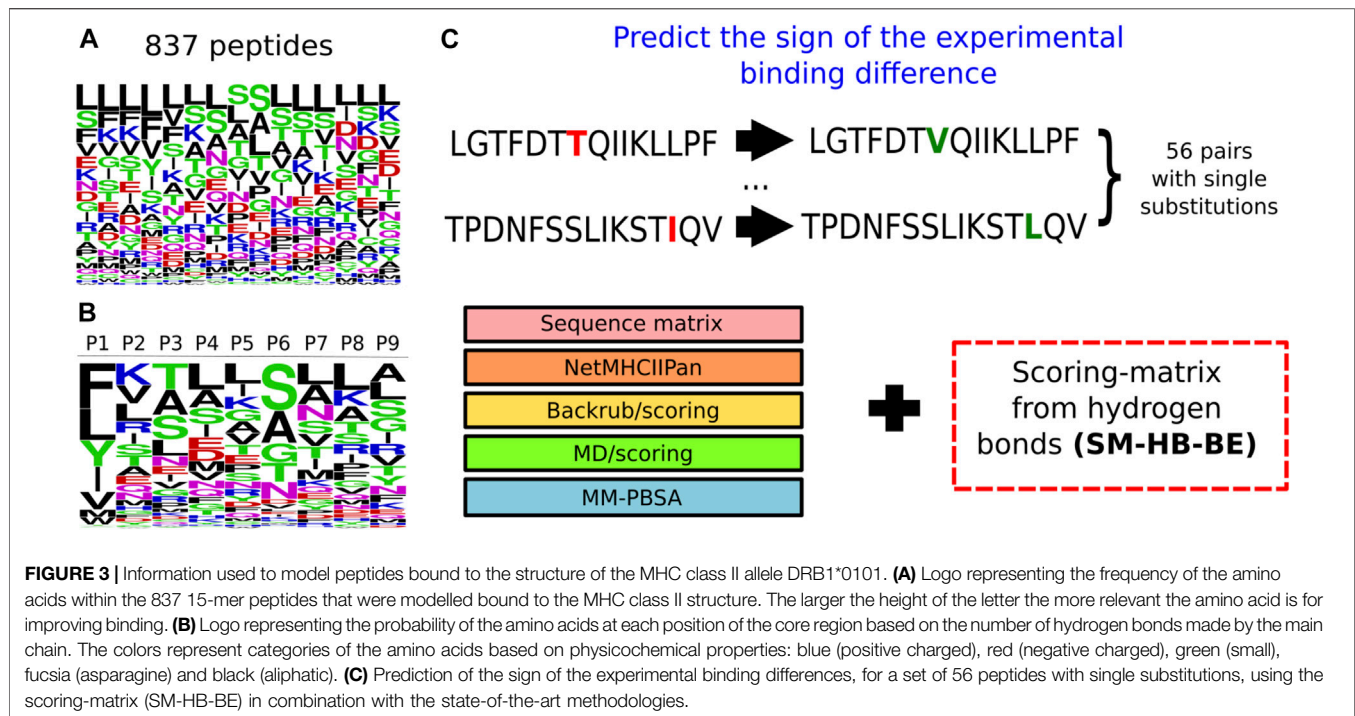


TABLE 3 | Prediction of the sign of the experimental activity differences by single-point mutations of the peptide core amino acids using the scoring-matrix calculated based on the hydrogen bonds made by main chain atoms (SM-HB) and the number of non-bonded contacts (SM-C). The comparisons include data for the four strategies to extract information from the 2,000 backrub frames.

Strategy	Matches for SM-HB (%)	Matches for SM-C (%)
All the frames	0.553	0.501
Last half frames	0.518	0.464
Half frames with best energies	0.589	0.501
Best energy frame	0.464	0.518

The prediction results were assessed using the SM-HB and SM-C matrices with a different number and type of frames selected from the backrub trajectories. Specifically, the matrices were obtained using all the frames, the last half of the frames, half frames with best energy-scores and the single best energy frame after optimization (see Methods). A summary of the performances to predict the sign of the activity differences is shown in **Table 3**.

We find that, in general, the observable with the highest number of correct predictions is the SM-HB, in comparison with the SM-C. In particular, for the SM-HB, the best performance was 58.9% using half of the frames with the best predicted energies based on the Rosetta scoring function (henceforth SM-HB-BE with “BE” for best energies). To complement the analysis, we calculated the scoring-matrices six times by dividing the original 837 peptide set into six independent sets. With these matrices, we calculated the mean and standard deviation of the number of matches against the experimental data (see **Supplementary Table S3**). In agreement

with the results shown in **Table 3**, we found that the selected SM-HB-BE has the best performance.

Prediction of Activity Differences for Methods That Range in Computational Costs

We compared the best structural scoring matrix (SM-HB-BE), to five previously benchmarked approaches to rank MHC class II peptide binders based on their predicted affinities, or based on the probabilities of finding certain amino acids in the peptide sequence (**Figure 3C**). These methods differ in the theory and, importantly, in their computational cost. In the case of the sequence-based methods, these are able to predict affinities in just a few minutes, but they largely depend on the chemical space of the training data to be successful. The structure/dynamics-based methods range from days to weeks in computational costs. The latter do not rely on training datasets but on physical, chemical and dynamical properties. To assess these diverse

methodologies, we tested them to predict the sign of activity differences by single-point mutations as explained in Methods, and compared their computational cost by running them on an Intel Xeon 24-core server with NVIDIA Titan X GPU acceleration (Table 4). In addition, a bootstrapping approach with 50 replicas was ran using randomly, and with repetitions, any pair from the total 56 pairs mutated peptides, in order to obtain a standard deviation of the match for each strategy.

We found that SM-HB-BE has a similar but slightly better match than the main state-of-the-art method (NetMHCIIpan) and the structural MD/scoring and backrub/scoring approaches, but with lower computational times. In the case of MM-PBSA, the results are similar to the backrub/scoring method, but with a computational performance that is 150 times larger than the most efficient sequence-based method (which is inconvenient for large-scale analysis). Based on the results, it is possible to use some of these structural descriptors to pre-select mutations in the core region that could improve the binding affinity requiring low computational costs. We note that the implementation of the scoring-matrices is highly efficient due to its usage as sequence-based descriptors of a particular peptide. The same happens with the sequence-based matrix and the machine learning method. In this sense, using the backrub trajectories to calculate consensus average scores is the most efficient alternative, based on time differences between a few hours to weeks taken by the backrub method and MD simulations (Table 4).

We also studied if for certain mutations their activity differences are more difficult to predict. We found that those involving arginine and charged amino acids are more challenging. In addition, amino acids changing drastically in size can misguide the predictions for the majority of the methods. A list of the cases where most of the methods fail is shown in Supplementary Table S4. Overall, these results indicate that predicting the activity differences of single-point mutations of peptides bound to MHC class II is challenging, even using extensive calculations such as MM-PBSA.

Combining Structural Scoring-Matrices With Alternative Methodologies Improves the Affinity Difference Prediction

Because there is still room to improve the affinity-difference prediction, we combined the results of each additional method with the SM-HB-BE. The combination consists on checking if either of the two methods predicts a positive mutation, if so then the mutation has a match with the experimental data. This allow us to verify which method complements better with the selected scoring-matrix (Table 5). We also included the standard deviations of the matches by following the same bootstrapping approach explained in the previous section.

We found that combining SM-HB-BE with the MD/scoring approach can predict correctly 85.7% of the mutations included in the study, followed by a 78.6% using the backrub/scoring and the MM-PBSA methodologies. As seen, the best results are found after combining the scoring-matrices with structure/dynamic-based strategies, but such combination can be done with the backrub/scoring approach that is more computationally efficient

TABLE 4 | Match values and bootstrapping standard deviations for the prediction of the sign of the experimental activity differences by single-point mutations of the peptide core amino acids for five state-of-the-art methodologies and the SM-HB-BE (i.e., scoring matrix from hydrogen bonds using half of the conformations with best energies). In addition, we include the computational costs, in days, for running the methods with the 56 pairs of mutated peptides. The strategies are the sequence motif matrix, the machine learning tool NetMHCIIpan, the MD/scoring and backrub/scoring approaches, and the MM-PBSA calculations (see Methods).

Complementary strategy	Matched predictions	Computational cost (days)
Sequence matrix	0.393 ± 0.067	0.05
NetMHCIIpan	0.536 ± 0.079	0.1
Backrub/scoring	0.536 ± 0.067	2
MD/scoring	0.571 ± 0.071	15
MM-PBSA	0.518 ± 0.062	15
SM-HB-BE scoring matrix	0.589 ± 0.065	0.05

(Table 4). In any case, the calculated scoring-matrices can improve information about the frequency of amino acids in core positions using motif representations, and overall the performance is higher than using the sequence-based matrices available in the literature (Rapin et al., 2008).

DISCUSSION

We evaluated the role of structural observables from simulations for predicting activity differences caused by single-point mutation of MHC class II peptide binders. A scoring-matrix derived from counting the number of hydrogen bonds formed by the main chain atoms using the best Rosetta energies (SM-HB-BE), can significantly improve the prediction of these differences if combined with other sequence or simulation-based methodologies.

To deal with the number of modelled peptides, we required running an efficient methodology for sampling the conformations as closely as possible to their equilibrium ensemble. After optimizing the Monte Carlo backrub parameters, we obtained similar conformations to those explored by MD simulations. We note that the MD simulation time was chosen based on previous assessments for exploring well the conformations around the mutated complex, which is around 20 ns for this system (Ochoa et al., 2019; Ochoa et al., 2020). The backrub method tends to perform a similar exploration of the formation of certain contacts and hydrogen bonds, mostly those created by the core region of the peptide. Moreover, the RMSD values between conformations from MD vs backrub are indistinguishable from those of MD vs MD. However, we note that the method is unable to reproduce completely the landscape explored by MD, which can be a limitation. This is why starting from a crystallized bound-conformation is critical for providing more reliable poses of the modelled peptides. Regarding the computational time, the backrub method can sample a similar number of frames as MD in just a few hours, in comparison to days required for MD in high-computing infrastructures (Table 4). This facilitates the analysis of a large set of peptides

TABLE 5 | Match values and bootstrapping standard deviations for the prediction of the sign of the experimental activity differences by single point mutations of the peptide core amino acids. The results are for the combination of the additional methodologies with the SM-HB-BE matrix. The strategies are the sequence motif matrix, the machine learning tool NetMHCIIpan, the MD/scoring and backrub/scoring approaches, and the MM-PBSA calculations (see Methods).

Complementary strategy	Matched predictions in combination with the SM-HB-BE matrix
Sequence matrix	0.607 ± 0.062
NetMHCIIpan	0.714 ± 0.064
Backrub/scoring	0.786 ± 0.051
MD/scoring	0.857 ± 0.047
MM-PBSA	0.786 ± 0.048

for this MHC class II allele, and others with structures available in public databases.

The peptide were selected based on criteria that facilitate the initial modelling of the rotamers (Ochoa et al., 2018), and the inclusion, in some cases, of additional flanking amino acids. Moreover, these peptides have available experimental binding data. Therefore, the new descriptors contain intrinsic information about the distribution of amino acids based on binding information, implying that our structural insights are complementing the known sequence-based motifs (Menconi et al., 2008; Andreatta et al., 2012). This is relevant because our protocol does not start from scratch. Instead, its main goal is to exploit the current knowledge of the system, and provide better metrics for the understanding of the MHC class II binding using simulations.

The calculated observables can be compared to the reported MHC class II promiscuity in terms of the intrinsic stability of the interactions between the peptide and the MHC class II binding groove. We found, for example, that the hydrogen bonds created by the main chain atoms are one of the most important structural observables. This claim has also been proposed in other studies, motivated by the stability of the peptide-bound conformation in spite of being completely linear, which is crucial in the molecular editing processes within the antigen presentation pathways (Painter et al., 2008; Yaneva et al., 2010; Ferrante et al., 2015). Therefore, simulating the dynamics of the complex can bring novel insights into the binding nature, and allows us to predict activity differences caused by single-point substitutions on the peptide sequence.

CONCLUSION

Simulations provide structural insights for creating simple scoring-matrices that complement available methods to better predict the effect of single-mutations on the binding of peptides to MHC class II molecules. Integrating sequence, structural and dynamical information is useful to progress in the immunoinformatics field, not only for MHC class II structures, but also for other key components within the immune response pathways.

Moreover, the methodology can contribute to the identification of epitopes for certain alleles using structural and dynamical information. In fact, the method can be expanded to calculate descriptors for other peptide-binding

complexes, to design of novel epitopes by single-point substitutions, and to understand the impact of antigen mutations in the immune system, for example, using structural interactions with the T-cell receptors, having direct consequence in vaccine design (Purcell et al., 2007). The descriptors can also help to, possibly, discriminate at a reasonable level between good binders and non-binders. However, a better discrimination requires combining multiple methods, or implement more exhaustive approaches to capture the chemical contributions of the peptide residues through more explicit free energy calculations (Wieczorek et al., 2016; Huang et al., 2017).

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://github.com/rochoa85/MHC_class_II_matrices, Github.

AUTHOR CONTRIBUTIONS

RO designed and ran the modelling and simulation computational protocols, created the code, and wrote the manuscript. RL tested the scoring matrices and the code, provided feedback and wrote the manuscript. JT provided feedback and wrote the manuscript. PC supported the computational analysis, provided feedback and wrote the manuscript.

FUNDING

This work has been supported by Colciencias, University of Antioquia and Ruta N, Colombia, the Max Planck Society, Germany and the CABANA initiative, United Kingdom.

ACKNOWLEDGMENTS

The authors thank AL for his advice in the methodology and result analysis. RO thanks the CABANA initiative for funding the secondment project during 2019. RO. and PC. were also supported by Colciencias, University of Antioquia, Ruta N,

Colombia and the Max Planck Society, Germany. The computations were performed on the EMBL-EBI cluster and on a local server with an NVIDIA Titan X GPU. PC gratefully acknowledges the support of the NVIDIA Corporation for the donation of this GPU.

REFERENCES

- Alford, R. F., Leaver-Fay, A., Jeliazkov, J. R., O'Meara, M. J., DiMaio, F. P., Park, H., et al. (2017). The Rosetta all-atom energy function for macromolecular modeling and design. *J. Chem. Theor. Comput.* 13, 3031–3048. doi:10.1021/acs.jctc.7b00125
- Andreatta, M., Karosiene, E., Rasmussen, M., Stryhn, A., Buus, S., and Nielsen, M. (2015). Accurate pan-specific prediction of peptide-MHC class II binding affinity with improved binding core identification. *Immunogenetics* 67, 641–650. doi:10.1007/s00251-015-0873-y
- Andreatta, M., Lund, O., and Nielsen, M. (2012). Simultaneous alignment and clustering of peptide data using a Gibbs sampling approach. *Bioinformatics* 29, 8–14. doi:10.1093/bioinformatics/bts621
- Andrusier, N., Nussinov, R., and Wolfson, H. J. (2007). FireDock: fast interaction refinement in molecular docking. *Proteins* 69, 139–159. doi:10.1002/prot.21495
- Antunes, D. A., Devaurs, D., Moll, M., Lizée, G., and Kavraki, L. E. (2018). General prediction of peptide-MHC binding modes using incremental docking: a proof of concept. *Sci. Rep.* 8, 4327. doi:10.1038/s41598-018-22173-4
- Aranha, M. P., Jewel, Y. S. M., Beckman, R. A., Weiner, L. M., Mitchell, J. C., Parks, J. M., et al. (2020). Combining three-dimensional modeling with artificial intelligence to increase specificity and precision in peptide-mhc binding predictions. *J. Immunol.* 205, 1962–1977. doi:10.4049/jimmunol.1900918
- Barlow, K. A., Ó Conchúir, S., Thompson, S., Suresh, P., Lucas, J. E., Heinonen, M., et al. (2018). Flex ddG: Rosetta ensemble-based estimation of changes in protein-protein binding affinity upon mutation. *J. Phys. Chem. B* 122, 5389–5399. doi:10.1021/acs.jpcc.7b11367
- Berman, H. M., Westbrook, J., Feng, Z., Gilliland, G., Bhat, T. N., Weissig, H., et al. (2000). The protein data bank. *Nucleic Acids Res.* 28, 235–242. doi:10.1093/nar/28.1.235
- Bermúdez, A., Calderon, D., Moreno-Vranich, A., Almonacid, H., Patarroyo, M. A., Poloche, A., et al. (2014). Gauche+ side-chain orientation as a key factor in the search for an immunogenic peptide mixture leading to a complete fully protective vaccine. *Vaccine* 32, 2117–2126. doi:10.1016/j.vaccine.2014.02.003
- Berrera, M., Molinari, H., and Fogolari, F. (2003). Amino acid empirical contact energy definitions for fold recognition in the space of contact maps. *BMC Bioinform.* 4, 8. doi:10.1186/1471-2105-4-8
- Bjorkman, P. J. (2015). Not second class: the first class II MHC crystal structure. *J. Immunol.* 194, 3–4. doi:10.4049/jimmunol.1402828
- Bogan, A. A., and Thorn, K. S. (1998). Anatomy of hot spots in protein interfaces. *J. Mol. Biol.* 280, 1–9. doi:10.1006/jmbi.1998.1843
- Cock, P. J. A., Antao, T., Chang, J. T., Chapman, B. A., Cox, C. J., Dalke, A., et al. (2009). Biopython: freely available Python tools for computational molecular biology and bioinformatics. *Bioinformatics* 25, 1422–1423. doi:10.1093/bioinformatics/btp163
- Cossio, P., Granata, D., Laio, A., Seno, F., and Trovato, A. (2012). A simple and efficient statistical potential for scoring ensembles of protein structures. *Sci. Rep.* 2, 1–8. doi:10.1038/srep00351
- Crooks, G. E., Hon, G., Chandonia, J. M., and Brenner, S. E. (2004). WebLogo: a sequence logo generator. *Genome Res.* 14, 1188–1190. doi:10.1101/gr.849004
- Davis, I. W., Arendall, W. B., Richardson, D. C., and Richardson, J. S. (2006). The backbone motion: how protein backbone shrugs when a sidechain dances. *Structure* 14, 265–274. doi:10.1016/j.str.2005.10.007
- Dominguez, C., Boelens, R., and Bonvin, A. M. J. J. (2003). HADDOCK: a protein docking approach based on biochemical or biophysical information. *J. Am. Chem. Soc.* 125, 1731–1737. doi:10.1021/ja026939x
- Ferrante, A., Templeton, M., Hoffman, M., and Castellini, M. J. (2015). The thermodynamic mechanism of peptide-MHC class II complex formation is a determinant of susceptibility to HLA-DM. *J. Immunol.* 195, 1251–1261. doi:10.4049/jimmunol.1402367

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmolb.2021.636562/full#supplementary-material>.

- Fogolari, F., Corazza, A., Yarra, V., Jalaru, A., Viglino, P., and Esposito, G. (2012). Blues: a program for the analysis of the electrostatic properties of proteins based on generalized born radii. *BMC Bioinformatics* 13, S18. doi:10.1186/1471-2105-13-S4-S18
- Hershey, J. R., and Olsen, P. A. (2007). Approximating the Kullback-Leibler divergence between Gaussian mixture models. *IEEE Int. Conf. Acoust. Speech Signal Process.* 7, 317–320. doi:10.1109/ICASSP.2007.366913
- Hess, B., Kutzner, C., van der Spoel, D., and Lindahl, E. (2008). GROMACS 4: algorithms for highly efficient, load balanced, and scalable molecular simulations. *J. Chem. Theor. Comput.* 4, 435–447. doi:10.1021/ct700301q
- Hopf, T. A., Ingraham, J. B., Poelwijk, F. J., Schärfe, C. P. I., Springer, M., Sander, C., et al. (2017). Mutation effects predicted from sequence co-variation. *Nat. Biotechnol.* 35, 128–135. doi:10.1038/nbt.3769
- Huang, M., Huang, W., Wen, F., and Larson, R. G. (2017). Efficient estimation of binding free energies between peptides and an MHC class II molecule using coarse-grained molecular dynamics simulations with a weighted histogram analysis method. *J. Comput. Chem.* 38, 2007–2019. doi:10.1002/jcc.24845
- Huang, P.-S., Ban, Y.-E. A., Richter, F., Andre, I., Vernon, R., Schief, W. R., et al. (2011). RosettaRemodel: a generalized framework for flexible backbone protein design. *PLoS One* 6, e24109. doi:10.1371/journal.pone.0024109
- Kastritis, P. L., and Bonvin, A. M. J. J. (2010). Are scoring functions in protein docking ready to predict interactomes? Clues from a novel binding affinity benchmark. *J. Proteome Res.* 9, 2216–2225. doi:10.1021/pr9009854
- King, C. A., and Bradley, P. (2010). Structure-based prediction of protein-peptide specificity in Rosetta. *Proteins* 78, 3437–3449. doi:10.1002/prot.22851
- Krissinel, E., and Henrick, K. (2007). Inference of macromolecular assemblies from crystalline state. *J. Mol. Biol.* 372, 774–797. doi:10.1016/j.jmb.2007.05.022
- Kuhlman, B., and Bradley, P. (2019). Advances in protein structure prediction and design. *Nat. Rev. Mol. Cell Biol.* 20, 681–697. doi:10.1038/s41580-019-0163-x
- Kumari, R., Kumar, R., Lynn, A., and Lynn, A. (2014). g_mmpbsa: a GROMACS tool for high-throughput MM-PBSA calculations. *J. Chem. Inf. Model.* 54, 1951–1962. doi:10.1021/ci500020m
- Lanzarotti, E., Marcatili, P., and Nielsen, M. (2018). Identification of the cognate peptide-MHC target of T cell receptors using molecular modeling and force field scoring. *Mol. Immunol.* 94, 91–97. doi:10.1016/j.molimm.2017.12.019
- Li, M., Petukh, M., Alexov, E., and Panchenko, A. R. (2014). Predicting the impact of missense mutations on protein-protein binding affinity. *J. Chem. Theor. Comput.* 10, 1770–1780. doi:10.1021/ct401022c
- Löffler, P., Schmitz, S., Hupfeld, E., Sterner, R., Merkl, R., and Hughes, M. (2017). RosettaMSF: a modular framework for multi-state computational protein design. *PLoS Comput. Biol.* 13, e1005600. doi:10.1371/journal.pcbi.1005600
- McDonald, I. K., and Thornton, J. M. (1994). Satisfying hydrogen bonding potential in proteins. *J. Mol. Biol.* 238, 777–793. doi:10.1006/jmbi.1994.1334
- Menconi, F., Monti, M. C., Greenberg, D. A., Oashi, T., Osman, R., Davies, T. F., et al. (2008). Molecular amino acid signatures in the MHC class II peptide-binding pocket predispose to autoimmune thyroiditis in humans and in mice. *Proc. Natl. Acad. Sci.* 105, 14034–14039. doi:10.1073/pnas.0806584105
- Nandy, A., and Basak, S. (2016). A brief review of computer-assisted approaches to rational design of peptide vaccines. *Int. J. Mol. Sci.* 17, 666. doi:10.3390/ijms17050666
- Nielsen, M., Lund, O., Buus, S., and Lundegaard, C. (2010). MHC Class II epitope predictive algorithms. *Immunology* 130, 319–328. doi:10.1111/j.1365-2567.2010.03268.x
- Ochoa, R., Soler, M., Laio, A., and Cossio, P. (2020). Parce: protocol for amino acid refinement through computational evolution. *Comput. Phys. Commun.* 260, 107716. doi:10.1016/j.cpc.2020.107716
- Ochoa, R., Laio, A., and Cossio, P. (2019). Predicting the affinity of peptides to major histocompatibility complex class II by scoring molecular dynamics simulations. *J. Chem. Inf. Model.* 59, 3464–3473. doi:10.1021/acs.jcim.9b00403

- Ochoa, R., Soler, M. A., Laio, A., and Cossio, P. (2018). Assessing the capability of in silico mutation protocols for predicting the finite temperature conformation of amino acids. *Phys. Chem. Chem. Phys.* 20, 25901–25909. doi:10.1039/C8CP03826K
- Omasits, U., Knapp, B., Neumann, M., Steinhauser, O., Stockinger, H., Kobler, R., et al. (2008). Analysis of key parameters for molecular dynamics of pMHC molecules. *Mol. Simul.* 34, 781–793. doi:10.1080/08927020802256298
- Painter, C. A., Cruz, A., López, G. E., Stern, L. J., and Zavala-Ruiz, Z. (2008). Model for the peptide-free conformation of class II MHC proteins. *PLoS One* 3, e2403. doi:10.1371/journal.pone.0002403
- Peters, B., Nielsen, M., and Sette, A. (2020). T cell epitope predictions. *Annu. Rev. Immunol.* 38, 123–145. doi:10.1146/annurev-immunol-082119-124838
- Purcell, A. W., McCluskey, J., and Rossjohn, J. (2007). More than one reason to rethink the use of peptides in vaccine design. *Nat. Rev. Drug Discov.* 6, 404–414. doi:10.1038/nrd2224
- Rapin, N., Hoof, I., Lund, O., and Nielsen, M. (2008). MHC motif viewer. *Immunogenetics* 60, 759–765. doi:10.1007/s00251-008-0330-2
- Sammond, D. W., Eletr, Z. M., Purbeck, C., Kimple, R. J., Siderovski, D. P., and Kuhlman, B. (2007). Structure-based protocol for identifying mutations that enhance protein-protein binding affinities. *J. Mol. Biol.* 371, 1392–1404. doi:10.1016/j.jmb.2007.05.096
- Sarti, E., Zamuner, S., Cossio, P., Laio, A., Seno, F., and Trovato, A. (2013). Bachscore. a tool for evaluating efficiently and reliably the quality of large sets of protein structures. *Comput. Phys. Commun.* 184, 2860–2865. doi:10.1016/j.cpc.2013.07.019
- Slutzki, M., Reshef, D., Barak, Y., Haimovitz, R., and Rotem-Bamberger, S. (2015). Crucial roles of single residues in binding affinity, specificity, and promiscuity in the cellulosomal cohesin-dockerin interface. *J. Biol. Chem.* 290, 13654–13666. doi:10.1074/jbc.M115.651208
- Smith, C. A., and Kortemme, T. (2008). Backrub-like backbone simulation recapitulates natural protein conformational variability and improves mutant side-chain prediction. *J. Mol. Biol.* 380, 742–756. doi:10.1016/j.jmb.2008.05.023
- Smith, C. A., and Kortemme, T. (2010). Structure-based prediction of the peptide sequence space recognized by natural and synthetic PDZ domains. *J. Mol. Biol.* 402, 460–474. doi:10.1016/j.jmb.2010.07.032
- Tokuriki, N., Stricher, F., Schymkowitz, J., Serrano, L., and Tawfik, D. S. (2007). The stability effects of protein mutations appear to be universally distributed. *J. Mol. Biol.* 369, 1318–1332. doi:10.1016/j.jmb.2007.03.069
- Trott, O., and Olson, A. J. (2009). AutoDock Vina: improving the speed and accuracy of docking with a new scoring function, efficient optimization, and multithreading. *J. Comput. Chem.* 31, 455–461. doi:10.1002/jcc.21334
- Unanue, E. R., Turk, V., and Neefjes, J. (2016). Variations in MHC class II antigen processing and presentation in health and disease. *Annu. Rev. Immunol.* 34, 265–297. doi:10.1146/annurev-immunol-041015-055420
- Wang, P., Sidney, J., Dow, C., Mothé, B., Sette, A., and Peters, B. (2008). A systematic assessment of MHC class II peptide binding predictions and evaluation of a consensus approach. *PLoS Comput. Biol.* 4, e1000048. doi:10.1371/journal.pcbi.1000048
- Wang, P., Sidney, J., Kim, Y., Sette, A., Lund, O., Nielsen, M., et al. (2010). Peptide binding predictions for HLA DR, DP, and DQ molecules. *BMC Bioinform.* 11, 568. doi:10.1186/1471-2105-11-568
- Wieczorek, M., Abualrous, E. T., Sticht, J., Álvaro-Benito, M., Stolzenberg, S., Noé, F., et al. (2017). Major histocompatibility complex (MHC) class I and MHC class II proteins: conformational plasticity in antigen presentation. *Front. Immunol.* 8, 1–16. doi:10.3389/fimmu.2017.00292
- Wieczorek, M., Sticht, J., Stolzenberg, S., Günther, S., Wehmeyer, C., El Habre, Z., et al. (2016). MHC Class II complexes sample intermediate states along the peptide exchange pathway. *Nat. Commun.* 7, 13224. doi:10.1038/ncomms13224
- Yaneva, R., Schneeweiss, C., Zacharias, M., and Springer, S. (2010). Peptide binding to MHC class I and II proteins: new avenues from new methods. *Mol. Immunol.* 47, 649–657. doi:10.1016/j.molimm.2009.10.008
- Yang, Y., and Zhou, Y. (2008). Specific interactions for ab initio folding of protein terminal regions with secondary structures. *Proteins* 72, 793–803. doi:10.1002/prot.21968
- Yeturu, K., Utriainen, T., Kemp, G. J., and Chandra, N. An automated framework for understanding structural variations in the binding grooves of MHC class II molecules. *BMC Bioinform.* 11 (2010) S55. doi:10.1186/1471-2105-11-S1-S55
- Zhang, H., Wang, P., Papangelopoulos, N., Xu, Y., Sette, A., Bourne, P. E., et al. (2010). Limitations of ab initio predictions of peptide binding to MHC class II molecules. *PLoS One* 5, e9272. doi:10.1371/journal.pone.0009272
- Zhou, H., and Skolnick, J. (2011). GOAP: a generalized orientation-dependent, all-atom statistical potential for protein structure prediction. *Biophys. J.* 101, 2043–2052. doi:10.1016/j.bpj.2011.09.012

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2021 Ochoa, Laskowski, Thornton and Cossio. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.