Structural glycobiology of the major allergen of *Artemisia vulgaris* pollen, Art v 1: O-glycosylation influence on the protein dynamics and allergenicity

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Art v 1 is the major allergen of mugwort (*Artemisia vulgaris*) pollen. It is formed by an N-terminal globular defensin-like part and a C-terminal proline-rich domain. As the structure and the dynamics of Art v 1 have been mostly described for its recombinant, non-glycosylated form, which does not occur in normal plant physiology, the present work intends to obtain a three-dimensional model for Art v 1 native O-glycosylation structure and to evaluate the influence of such glycans over the protein dynamics and allergenicity through molecular dynamics simulations in triplicates. Structural insights into the mutual recognition of Art v 1 protein and carbohydrate moieties recognition by antibodies were obtained, in which glycan chains remained close to the previously identified epitopes in the defensin-like domain, thus pointing to potential interferences with antibodies recognition. To our knowledge, this is the first structural report of an entire furanose-containing glycoprotein. As well, together with the previously determined NMR structures, the obtained results contribute in the comprehension of the effect of glycosylation over both proline-rich and defensin-like domains, providing an atomic representation of such alterations.

**Keywords:** allergy / antibody recognition / arabinofuranose / glycosidic linkage / molecular dynamics

**Introduction**

Art v 1 is the major allergen of mugwort (*Artemisia vulgaris*) pollen (Gadermaier et al. 2004), which is a widely spread plant in temperate and humid zones of the Northern hemisphere and along the Mediterranean Basin (Spieksma et al. 1980). Structurally, Art v 1 is a 108-amino acid glycoprotein formed by two domains (Himly et al. 2003). At the N-terminal, there is a globular defensin-like, disulfide-bond rich structural unit, which is the main target of IgE antibodies in atopic individuals (Himly et al. 2003; Dedic et al. 2009) and contains the main epitope for T-cell recognition (Jahn-Schmid et al. 2002). Conversely, a proline-rich domain containing several (Ser/Ala)-(Pro)₂-₄ extensin-like repeats is located at Art v 1 C-terminal, which is post-translationally modified through proline 4-hydroxylation and O-glycosylation (Himly et al. 2003).

The 4-hydroxyproline (HyP) residues at the C-terminal domain may be added by two types of glycans: the most abundant consist of single β-arabinofuranoses, also partially or mainly recognized by antibodies in the subgroups of *Artemisia*-allergic patients (Himly et al. 2003; Leonard et al. 2005); and the less abundant comprises a large arabinogalactan, composed of three galactopyranose (Galp) and at least 10 arabinofuranose (Araf) residues (Himly et al. 2003; Leonard et al. 2005). Accordingly, Art v 1 may be found in a minor prevalence 13-kDa glycoform, only presenting β-Araf-linked glycans, or in the mainly occurring 15 kDa glycosylation state, also containing, beyond β-Araf, one or two arabinogalactan oligosaccharides (Himly et al. 2003). Although such glycans may represent from 30 to 50% of the mature protein molecular mass, mostly no three-dimensional (3D) information is available for them, and Art v 1 protein moiety could only be completely solved in its recombinant form through NMR techniques in the absence of O-linked glycans (Razzera et al. 2009). From such assignments, it could be observed that, although the defensin-like domain shows a relatively unvariable conformation, its C-terminal part presents a high flexibility (Razzera et al. 2010), thus assuming several conformational states. As well, distinct chemical shifts have been identified for some regions of the recombinant (non-glycosylated) and natural (glycosylated) Art v 1 (Razzera et al. 2010), although the structural source of these differences could not be distinguished.

In this context, the current work intends to obtain a 3D model for the completely glycosylated Art v 1 O-linked and to evaluate the effects of glycosylation over the structure and dynamics of its protein moiety through molecular dynamics (MD) simulations in aqueous solutions. The oligosaccharides
were assessed and constructed based on their composing disaccharidic units, through energy contour maps and solution MD simulations conformational sampling. The obtained glycan chains were attached to the protein core and further refined through MD. The obtained results were discussed in terms of the differences between Art v 1 non-glycosylated and glycosylated forms, as well as its (hydroxy)proline-rich domain flexibility and dynamics. Such results were compared with experimental data, mainly derived from NMR results, supporting further insights into glycosylation role on Art v 1 dynamics and allergenicity.

Results

Systems preparation

In order to explore Art v 1 conformation and flexibility in aqueous solutions, including its glycan chains, we have studied such protein in increasing complexity levels, from non-glycosylated states, containing either Pro or HyP in the C-terminal segment, to both its minor and major prevalence glycoforms. Additionally, in order to provide a higher conformational sampling, each condition was assessed in triplicates, each one starting from a distinct protein conformation, as derived from clustering analysis based on NMR data (Razzera et al. 2010). Six non-glycosylated systems were simulated, being three for Pro-containing structures and three for Art v 1 containing HyP residues. Six systems were assembled for an Art v 1 minor prevalence glycoform, thus lacking the arabinogalactan oligosaccharide, but presenting mono-β-Araf at every HyP located within (Ser)-(HyP)_{2-4} motifs. Three of these structures contained Araf in its 1_{T2} form, and the other three presented such residue in its 4_{T3} conformation. Finally, the Art v 1 major prevalence glycoform was considered in six additional systems, also accounting for both Araf-puckering states, presenting the arabinogalactan glycan linked to HyP79 (see the Materials and methods section) and mono-β-Araf at all other HyP residues within (Ser)-(HyP)_{2-4} peptides.

Concerning Art v 1-glycosylated states, mostly no 3D data were available for constructing its O-linked glycans (Himly et al. 2003; Leonard et al. 2005). In this context, for the structures of the large arabinogalactan oligosaccharide (Figure 1A) and the mono-β-Araf (Figure 1B), considering both φ-ψ and ω-ψ combinations and varying the Araf puckering in its two possible conformations (i.e. 1_{T2} and 4_{T3}), 3 O-glycosidic linkages (between monosaccharides and 4-HyP) and 12 disaccharides were studied through energy contour maps and MD
(Supplementary data, Figure S1). Based on the main conformational states obtained from those glycosidic-linkage solution trajectories, the large arabinogalactan oligosaccharides were built and, together with the mono-β-Araf, were added to the Art v 1 protein structure. The data from disaccharides explicit solvent simulations were chosen for this purpose due to their capability to adequately represent the conformation of complex oligosaccharides (Naidoo et al. 1997; Kirchner and Woods 2001; Almond and Sheehan 2003; Elklund and Widmalm 2003; González-Outeiriño et al. 2005; Fernandes et al. 2010; Pol-Fachin et al. 2010).

**Glycosidic-linkage conformational profile**

Based on the data presented in Supplementary data, Figure S1 and Table I, it may be observed that all the α-anomers preceded by Araf residues were mainly populated at negative φ values, independently on the furanose-puckering form, as previously observed for the α-Araf(1 → 5)-Araf in previous works (Cros et al. 1994; Pérez et al. 2000). Regarding (1 → 5) and (1 → 6) linkages, the φ angle only adopted three main conformational peaks (Supplementary data, Figure S1H, N, O, R and S), around −180°, −60° and 60°, in accordance with Shefter and Trueblood’s convention (Shefter and Trueblood 1965). Although only minor differences in glycosidic-linkage geometries were observed between disaccharides presenting distinct Araf-puckering states, the global shape of the complete arabinogalactan oligosaccharides, when composed by such conformations, is quite different (Figure 1C and D). Furthermore, from both disaccharides and glycoproteins MD simulations, as presented in Table I, no major differences within standard deviations were observed when comparing glycosidic linkages on different complexity levels, i.e. either as isolated disaccharides or composing glycoproteins, as previously observed for N-glycans composing disaccharides (Fernandes et al. 2010).

**Effects of glycosylation over Art v 1 protein moiety structure and dynamics**

For all the glycosylation states and systems evaluated, the defensin-like domain maintained its original secondary structure content, as monitored by PROCHECK analyses (Supplementary data, Figure S2), as well as its tertiary structure and globularity during MD simulations (Supplementary data, Figure S3). In addition, interconversions could not be observed within the simulated time scale between the three clusters of conformations derived from the NMR data in either of the simulated conditions, as evaluated by performing clustering analyses with the same cut-off value employed under the available NMR models (see Materials and methods section).

Regarding the (Ser)-(Pro)₄ extensin-like motifs conformation, only point differences between the evaluated conditions could be observed as a consequence of mono-β-arabinosyla-

**O-Glycosylation over Art v 1 dynamics and allergenicity**

The proliferative T cell response to “mugwort” pollen has been recognized to mainly occur due to a single Art v 1 immunodominant epitope, comprising residues 25–36 (Jahn-Schmid et al. 2002). From NMR experiments, two B cell, IgE-recognized epitopes could be also identified, mostly located within the Art v 1 defensin-like domain, each one...
A group of patients suffering from pollinosis have been also identified, which, although still binding to the glycosylated form, present lower or no reactivity to recombinant Art v 1, which suggests an important role of its O-glycans for IgE binding (Himly et al. 2003). As derived from the performed MD simulations, several intramolecular contact differences between non-glycosylated and glycosylated Art v 1 systems could be observed, possibly interfering with antibody recognition (Figure 3). Accordingly, during the trajectories starting from clusters 1 and 3, the 102–105-linked oligosaccharides stood beside the Ser14-Arg40-Glu41-Glu45-Ser46 epitope (Figure 3A1 and C1). Additionally, elements of 79–80 and 86–89 glycan chains came close to the epitope composed by the residues Ser3-Lys4-Lys55-Ser56-Ala63 (Figure 3B1).

**Discussion**

Although it has been proposed that half of known proteins are potentially glycosylated (Apweiler et al. 1999; Ben-Dor et al. 2004), the structure and conformation of glycoproteins have been studied in only a very small number of works (Pol-Fachin and Verli 2011). Such glycans may affect several properties of their linked polypeptides, as folding and biological function (Pol-Fachin and Verli 2011). Although no
data are available about the role of Art v 1 glycan chains for plant physiology, the effects of glycosylation over its protein moiety structure, as well as over Art v 1 allergenicity, were previously described by NMR experiments (Razzera et al. 2010) and have been further explored by the present study. Accordingly, the NMR-derived results regarding the protein global structure, as secondary structure content, and Art v 1 mobility, as the transition state flexibility in comparison with the remaining C-terminal part, were employed for validating the obtained data, and the conformational source of some NMR chemical shift alterations, as due to glycosylation, could be proposed. Moreover, to our knowledge, this is the first structural report of an entire furanose-containing glycoprotein.

Regarding Art v 1 carbohydrate moieties, only minor differences could be observed in its glycosidic-linkage geometries and flexibilities as due to modifications in the AraF-puckering form. In this context, the 4T3 conformation appeared to allow the generation of minor prevalence conformational states in solution for some disaccharides (Supplementary data, Figure S1I in comparison with Supplementary data, Figure S1E; Supplementary data, Figure S1J in comparison with Supplementary data, Figure S1F) and to present a larger number of low-energy conformations in vacuum, especially in (1 → 5) and (1 → 6) linkages (Supplementary data, Figure S1M in comparison with Supplementary data, Figure S1L; Supplementary data, Figure S1Q in comparison with Supplementary data, Figure S1P), as a previously observed employing MM3 force field (Cros et al. 1994; Pérez et al. 2000). Such behavior indicates a higher conformational flexibility related to AraF-containing oligosaccharides when assuming the 4T3-puckering state. With reference to disaccharide-glycoprotein comparisons, no major differences in glycosidic-linkage geometries could be observed between the isolated structures and the entire O-linked glycans (Table I), suggesting that the protein moiety is not capable of inducing major conformational changes in its linked oligosaccharides, as proposed previously (Fernandes et al. 2010). Such data reinforce the suggestion that disaccharides solution conformations may

Fig. 2. RMSF analysis, as obtained from eigenvector 1 of PCA (see Materials and methods section) for the polyproline-rich domain, as analyzed from the entire MD simulations, starting from cluster 1 (B), cluster 2 (C) and cluster 3 (D). In the graphs, the 18 performed MDs are shown: non-glycosylated, containing Pro and HyP residues; O-glycosylated only with mono-β-AraF, in 1T2 or in 4T3 conformations; O-glycosylated with a large arabinogalactan oligosaccharide and with mono-β-AraF, accounting for both 1T2 and in 4T3 conformations.
be employed for constructing 3D models of protein-linked oligosaccharides.

In order to better comprehend Art v 1 protein moiety recognition by antibodies, chemical modifications (Perovic et al. 2009; Stanic et al. 2009) and site-directed mutagenesis studies (Gadermaier et al. 2010) have been conducted for Art v 1. Several studies have also been able to identify epitopes within other proteic plant allergen surfaces for IgE binding (Suphioglu et al. 1998; Flicker et al. 2006). Moreover, although glycosylation has also been identified as an important allergenic factor for Art v 1 (Himly et al. 2003), it is recognized that antibodies recognizing glycoprotein antigens may be specific for their carbohydrate units, irrespective of the protein carrier, or may mutually bind both peptidic and glycan moieties (Lisowska 2002). Accordingly, although the “sera” from patients presenting no reactivity to recombinant Art v 1 presumably only recognize its O-linked glycans, those showing reduced reactivity may also bind amino acid residues from either polyproline-rich or defensin-like domains. In this context, assuming that such shared recognition occur comprising amino acid residues composing the previously identified epitopes at its defensin-like domain, the data presented in the present work provide the first structural, atomic-level proposal for such binding. During MD simulations, several forcomings between defensin-like domain epitopes and glycan chains could be observed, which may suggest such regions as putative sites for O-linked glycans mutual recognition by IgEs: (i) Ser14-Arg40-Glu41-Glu45-Ser46 epitope and 102–105 glycans, which occurred almost systematically in eight independent MD simulations, and (ii) Ser3-Lys4-Lys55-Ser56-Ala63 residues and 79–80- and/or 86–89-linked oligosaccharides, occurring in four trajectories. Such data, together with previous studies on recombinant Art v 1 recognition by IgEs (Razzera et al. 2010) and HLA Class II/Peptide-TCR interactions (Jahn-Schmid et al. 2005, 2008), may be employed in the future for exploring natural, glycosylated, Art v 1 interactions with antibodies and the consequences of this binding to allergy triggering.

Concluding remarks

The comprehension of the mutual influence between bounded and/or unbounded protein and carbohydrate moieties is still a challenging task mainly due to the difficulties associated with the available experimental techniques in dynamically evaluate such interactions (Pol-Fachin and Verli 2011). In recent years, MD simulations have emerged as a promising tool, when combined with appropriate biochemical and structural experimental data, to study glycoproteins, glycoconjugates and protein–carbohydrate complexes in their biological solutions.

Fig. 3. Representative average distance matrices, consisting on the smallest distance between residue pairs, for glycosylated Art v 1 (A) cluster 1, (B) cluster 2 and (C) cluster 3 from MD trajectories. Gray points indicate no difference between non-glycosylated and glycosylated systems, and white and black indicate approximation and withdrawal in the glycosylated systems, respectively. In the structures, O-glycans are shown as sticks; the protein core is presented as cartoon; and the previously identified epitopes are illustrated as dots.
In the present study, we have built 3D models for the native Art v 1 glycoprotein, the major allergen of *A. vulgaris* pollen, and applied MD simulations in order to assess such protein–carbohydrate recognition. Accordingly, in conjunction with previous NMR experiments, an atomic-level representation of O-glycosylation effects over Art v 1 protein moiety could be obtained. Although to date most of the MD studies on glycoproteins reported N-linked oligosaccharides (Pol-Fachin and Becker et al. 2005; Pol-Fachin et al. 2009) and improper dihedrals in order to maintain the conformation of each monosaccharide in accordance with their aqueous solution, most abundant, expected forms: $^4C_1$ for $\alpha$-Gal and $^1T_2$ or $^4T_3$ for $\alpha$- and $\beta$-Ara (Hoffmann et al. 1992; Cros et al. 1993). Proper dihedrals, as described in GROMOS96 43a1 force field for glucose, were also included in the PRODRG-obtained topologies in order to support stable simulations for both Galp and Araf.

### Materials and methods

**Nomenclature and software**

The nomenclature recommendations and symbols were used as proposed by IUPAC (1996). The relative orientation of a pair of contiguous carbohydrate residues is described, for different types of linkages, by two or three torsional angles at the glycosidic linkage. For a (1→X) linkage, where “X” is “2”, “3”, “4”, “5” or “6” for the (1→2), (1→3), (1→4), (1→5) or (1→6) linkages, respectively, the $\phi$ and $\psi$ are defined as shown in equations below:

\[
\phi = O5 - C1 - O1 - CX \quad (1)
\]

\[
\psi = C1 - O1 - CX - C(X - 1) \quad (2)
\]

For a (1→6) linkage, the $\omega$ is defined as shown below:

\[
\omega = O1 - C6t - C5t - C4t \quad (3)
\]

Finally, for a (1→5) linkage, the $\omega$ is defined as shown below:

\[
\omega = O1 - C5t - C4t - C3t \quad (4)
\]

The manipulation of structures was performed with MOLDEN (Schaftenaar and Noordik 2000), VMD (Humphrey et al. 1996) and PyMol (The PyMOL Molecular Graphics System), the secondary structure content analyses were performed with PROCHECK (Laskowski et al. 1993) and all the MD calculations and the remaining analyses were performed using GROMACS simulation suite, version 4.5.1 (Hess et al. 2008), and GROMOS96 43a1 force field (Scott et al. 1999). Additionally, the (Ser)-Pro$_4$ extensin-like motif chirality was assessed via torsional handedness of the four consecutive Pro/HyP Cα atoms, also known as the $\zeta$ angle (Witte and Shakhnovich 1994).

**Topology construction for carbohydrate residues**

In order to perform a conformational description of Art v 1 glycan structures, their composing disaccharide fragments were constructed using MOLDEN software (Schaftenaar and Noordik 2000), as well as its constituents monosaccharides, Galp and Araf, in order to be used for such glycans building blocks within GROMACS package. These structures were described according to IUPAC (1996). The relative orientation of a pair of contiguous carbohydrate residues is described, for different types of linkages, by two or three torsional angles at the glycosidic linkage. For a (1→X) linkage, where “X” is “2”, “3”, “4”, “5” or “6” for the (1→2), (1→3), (1→4), (1→5) or (1→6) linkages, respectively, the $\phi$ and $\psi$ are defined as shown in equations below:

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Finally, for a (1→5) linkage, the $\omega$ is defined as shown below:

\[
\omega = O1 - C5t - C4t - C3t \quad (4)
\]

The conformational characterization of the glycosidic linkages composing Art v 1 glycan chains was initially performed by varying the $\phi$--$\psi$ and $\omega$--$\psi$ angles, formed by two consecutive monosaccharide residues, from $-180^\circ$ to $150^\circ$ with a $30^\circ$ step, in a total of 144 conformers for each linkage, as described previously (Becker et al. 2007). This was performed by using a constant force to restrict only the $\phi$ and $\psi$ proper dihedrals during energy minimization with conjugate gradients in each of the above-mentioned values, allowing the search of the conformational space associated with the given linkage. Then, using the minimized output geometries, a series of MD simulations was performed for 20 ps at 10 K, with an integration step of 0.5 fs, to further support the search for minimum-energy conformations (Pol-Fachin and Verli 2008). The relative stabilities of each conformation, obtained from the 10 K MD last frame, were therefore used to construct relaxed energy contour plots. Subsequently, each of the obtained energy maps was smoothed using SigmaPlot 11 software, employing the Loess smoother with a sampling proportion of 0.1 and a polynomial degree of 2. The minimum-energy conformations, obtained from such contour plots, were further refined through aqueous solutions MD simulations (see below).

**Principal component analysis**

The general idea of the PCA is to reduce the dimensionality of a given data set composed by interrelated variables, retaining as much as possible of the variation presented within it (Jolliffe 2002). For this purpose, the input data is transformed into a new set of variables, known as the principal components, which are uncorrelated, but are ordered so that the first few of them retain most of the variation contained within the original variables (Jolliffe 2002). In the case of the present work, the PCA was employed in order to better assess the high flexibility of the polyproline-rich domain, thus separating its main sources of motion into a new set of flexibility variables, that is, RMSF graphs. Therefore, instead of a single RMSF graph containing the global flexibility related to such domain, the eight eigenvectors obtained from such investigation through GROMACS suite were able to describe the main
sources of Art v 1 C-terminal part flexibility, being eigenvector 1 the principal flexibility basis around such domain.

Building of the glycosylated Art v 1 atomistic models
The Art v 1 glycosylated structures were constructed, as previously described (Pol-Fachin and Verli 2011), based on the combination of structural data for (1) its protein part, derived from the NMR solution data presented in PDB ID 2KPY (Razzera et al. 2010), comprising recombinant, non-glycosylated Art v 1; and for (2) its carbohydrate moiety, as described in the Glycosidic-linkage geometries assessment section. Regarding the protein moiety, due to the high flexibility related to the proline-rich domain, as observed from NMR experiments (Razzera et al. 2010), and in order to provide a higher conformational sampling for the evaluated systems, the 20 Art v 1 NMR models were clustered (employing g_cluster from GROMACS suite, with a 0.95-nm cutoff; Supplementary data, Table SIII) to obtain three groups (Supplementary data, Figure S5A) and allow each condition to be assessed as triplicates: (i) cluster 1 (including 15 models, represented by model 20); (ii) cluster 2 (including four models, represented by model 2); and (iii) cluster 3, represented by model 5 (Supplementary data, Figure S5B–D). Each of these clusters was represented in six conditions, to be explored through MD: (i) non-glycosylated, containing Pro residues at the C-terminal part of the protein; (ii) non-glycosylated, containing Hyp residues at the proline-rich domain; (iii) O-glycosylated with mono-β-Araf (Figure 1B) in all Hyp residues located within (Ser)-(HyP)2-4 motifs, in 1T2 or (iv) in 4T3 conformations; (v) O-glycosylated with a large arabinogalactan oligosaccharide (Figure 1A) at Hyp79 and with mono-β-Araf at the remaining (Ser)-(HyP)2-4, also accounting for both 1T2 and (vi) 4T3 conformations. The Hyp79 residue was chosen as the arabinogalactan glycosylation site due to the adequate arrangement and surface fitting of the oligosaccharide in relation to Art v 1 protein moiety when linked to such position (Supplementary data, Figure S5E–R). For the glycosylated systems, Art v 1 oligosaccharides were built based on the most prevalent geometries for its composing disaccharides, as obtained from solution MD simulations, being subsequently added to the protein structures.

MD simulations
The 18 Art v 1 starting structures, representing their different glycosylation states, as well as the minimum-energy conformations obtained from the energy maps for the disaccharides, were solvated in triclinic boxes using periodic boundary conditions and an SPC water model (Berendsen et al. 1987). Counter ions (Cl−) were added to neutralize the systems, whenever needed. The employed MD protocol was based on previous studies (de Groot and Grubmüller 2001), as described (Verli and Guimaraes 2004; Becker et al. 2005; Pol-Fachin et al. 2009). The Lincs method (Hess et al. 1997) was applied to constrain covalent bond lengths, allowing an integration step of 2 fs after an initial energy minimization using the Steepest Descents algorithm. Electrostatic interactions were calculated with the Particle Mesh Ewald method (Darden et al. 1993), and the dielectric constant was treated as e = 1. Temperature and pressure were kept constant by coupling (glyco)proteins or disaccharides, ions and solvent to external temperature and pressure baths with coupling constants of τ = 0.1 and 0.5 ps (Berendsen et al. 1984), respectively. The reference temperature was adjusted to 310 K after an initial and slow heating of the systems from 50 to 310 K, in steps of 5 ps, each one increasing the reference temperature by 50 K. Although each Art v 1 simulation was extended to 50 ns, the isolated disaccharides trajectories were extended to 0.1 μs.

Supplementary data
Supplementary data for this article is available online at http://glycob.oxfordjournals.org/.

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Conflict of interest
None declared.

Abbreviations
3D, three-dimensional; Araf, arabinofuranose; Galp, galactopyranose; Hyp, 4-hydroxyproline; MD, molecular dynamics; PCA, principal component analysis; RMSF, root-mean-square deviation.

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Berendsen HJC, Grigera JR, Straatsma TP. 1987. The missing term in effect-1. Temperature and pressure were kept constant by coupling (glyco)proteins or disaccharides, ions and solvent to external temperature and pressure baths with coupling constants of τ = 0.1 and 0.5 ps (Berendsen et al. 1984), respectively. The reference temperature was adjusted to 310 K after an initial and slow heating of the systems from 50 to 310 K, in steps of 5 ps, each one increasing the reference temperature by 50 K. Although each Art v 1 simulation was extended to 50 ns, the isolated disaccharides trajectories were extended to 0.1 μs.

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