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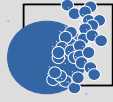
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Fragment-based modeling of protein-bound ssRNA

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BIOLOGICAL CONTEXT

Single-stranded (ss)RNA → **ssRNA-protein complex** ← **ssRNA-binding protein**

The structure of an RNA-protein complex is a key to:

- (i) understand its function or malfunction
- (ii) modulate or create it, for medicine or biotechnology

Experimental methods to obtain such structure (X-ray, NMR) are costly, time-consuming or limited to some complexes.

Therefore, it often requires computational modeling methods. Such methods exist for RNA-protein complexes, but fail at modeling **single-stranded RNA** because of their flexibility.

Incorrect → **Correct** → **Artificial**

- Disease**
 - Viral reproduction
 - Myogenic dystrophy
 - Degenerative diseases
- Biological function**
 - Transport of mRNA
 - Maturation of mRNA
 - Regulation of translation
- Drug**
 - Growth factor inhibitor
 - Anti-virus (C-hepatitis)
 - In vitro diagnosis

Key contacts for specificity

RATIONALE

Classical Docking

Experimentally known structures

Unbound protein

Unbound RNA

Unbound ssRNA

Ab initio Modeling

Modeling the RNA *in situ*, from its sequence

12 DOF to explore per nucleotide

Fewer correlations (constraints) than in double helix => combinatorial explosion for > 5-6 nucl.

RNA adopt discrete local conformations (= rotamers) => they can be represented by a finite number of structural fragments

Our alternative approach consists in modeling RNA local conformations and assemble them on the protein surface.

STRATEGY

RNA sequence: AUGGUC

Divided into overlapping trimers

Fragments library: AUG UGG GGU GUC

All possible local conformations. Extracted from structure databases

Protein structure: X-ray, NMR, ...

Predictable contacts

Conserved in protein family (optional)

Fragments docking

Parallel (if no known contacts) OR Sequential (if known contacts)

Positional restraints

Assembling

Identification of chains = spatially overlapping poses

CONCLUSION

Achievements

Our fragment-based approach to model protein-bound ssRNA proved effective to sample fragment poses at the surface of the protein. This permits to **predict the RNA binding site** with same sensitivity and higher specificity than all other binding-site prediction methods based on protein structure [3].

We can predict the orientation of nucleotides binding to **RNA-protein conserved contacts**, in the most abundant RNA-binding domains of proteins (RRM and PUF) [4].

With those anchoring nucleotides, we could model bound ssRNA up to **12-nucleotides** long, with a **resolution comparable to X-ray structures** [4].

Perspectives

We considered so far that we know which part of our RNA is single-stranded (ss) and binds the protein. In many real-cases, the RNA is partially structured (e.g. double-stranded, ds) or parts of it oscillate between ss and ds state. Moreover, the ss part binds the protein by only some of the nucleotides.

Therefore, we will include **RNA secondary structure prediction** methods together with **in vitro data** (e.g. SHAPE) to evaluate the likelihood of protein-binding for each nucleotide in the RNA of interest, before or within the docking process.

METHODS

Docking

ATTRACT docking engine [1,2]

- 1/ 10^7 random starting states (position * orientation * conformation)
- 2/ Energy minimisation of bead-bead interactions in an empirical force field
- 3/ Elimination of redundant poses (converged on same local minima)
- 4/ Ranking of poses by score (= pseudo-energy)

=> For each fragment: **best pose at 1 - 3 Å from X-ray structure among $10^2 - 10^3$ poses**

Assembling

Probabilistic

Systematic

Up to 10^6 poses per fragment

Pruning from each anchoring contact => Enumeration of all possible chains

Forward - backward paths count => Selection of the **most connected poses** (i.e. most probably part of the correct chain)

Scoring

Weights in final scoring

Chains are scored by the geometric mean of the ranking* of the poses.

This enhances the weight of very well-ranked poses, to account for hot-spots** in the RNA.

Score = $(\prod_{i \in [1, N]} \text{rank}(i))^{1/N}$

low score = good chain (hopefully)

* by pseudo-energy of protein-RNA interaction

** Fragments that bind with high energy (Often key parts for specific recognition)

Hierarchical clustering for efficient pruning

By distance

By computing the distance between the centers of two clusters, we assess if they could contain overlapping poses.

If yes, their subclusters are evaluated pairwise, and so on.

This spares pose-pose comparisons for pairs of poses belonging to distant clusters.

By best ranks

By assembling a small subset of poses, we estimate an upper limit of the best possible score.

We consider the best rank contained in each cluster.

For each pair of distance-compatible clusters, we check if the best possible score is acceptable. If yes, we go down to their sub-clusters.

Score < 25

$(300 \times 120)^{1/2} - 33$

$(2 \times 120)^{1/2} - 15$

RESULTS

Without predicted contacts

We blind-tested this approach on 2 complexes of known structure [3].

Filtering the poses by their chain-forming propensity (connectivity) enriches the pool in correct poses (RMSD < 5Å) more effectively than the docking score alone:

	Correct poses	Total
Docking score	1% - 4 %	$6 \cdot 10^5 - 1 \cdot 10^6$
Connectivity	10% - 13 %	$3 \cdot 10^3 - 8 \cdot 10^3$

More than 10% of poses are correct

With predicted contacts

We blind-tested this approach on 8 complexes of known structure [4].

We predicted the position and orientation of nucleotides establishing conserved contact, within 0.8 - 3.2 Å RMSD from the real structure (average 1.4 Å).

From those contacts, we modelled **5 to 7-nucl RNA within 2 Å RMSD** from the real structure, for 7 out of 8 complexes, among 130 to 270 proposed models.

By prolonging the RNA chain beyond the predicted contacts, we model **7 to 12-nucl RNA within 4 Å RMSD**.

Binding site prediction

In white: RNA position in X-ray structure

Nb of poses contacting each amino-acid

MODEL versus X-RAY

Predictions (pink) versus experimental structure (X-ray, white) of RNA bound to either a RRM domain (green, pdb-code 2CVJ) or a PUF domain (cyan, pdb-code 3BX3)

[1] de Vries SJ, Schindler C, Chauvot de Beauchêne I, Zacharias M. (2015) Biophys J.

[2] Setny P, Zacharias M. (2013) Nucleic Acids Research

[3] Chauvot de Beauchêne I, de Vries SJ, Zacharias M. (2016) PLoS.Comput.Biol.

[4] Chauvot de Beauchêne I, de Vries SJ, Zacharias M. (2016) Nucleic Acids Research

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