nature protocols

https://doi.org/10.1038/s41596-026-01356-8

Protocol

Check for updates

The trRosettaRNA server for RNA structure prediction

Supplementary Information

Supplementary Text 1. Architecture of updated trRosettaRNA.

As mentioned in the main text, the trRosettaRNA framework has been updated since its initial release, involving the simplified MSA search, in-house secondary structure (SS) predictor, and the end-to-end inference, etc. This section provides further details on two major components: our new in-house SS predictor (trRNA-SS) and the implementation of the end-to-end prediction module.

trRNA-SS. The original trRosettaRNA relied on SS predictions from SPOT-RNA. To ensure methodological independence and improve performance, we developed a new in-house SS predictor named trRNA-SS. This predictor takes an MSA as input, employs a stack of 8 RNAformer blocks (RNAformer was introduced in the original trRosettaRNA paper [1]), and outputs a predicted base-pairing probability map.

trRNA-SS was trained using a transfer-learning framework. The model was first pre-trained on 14,648 non-redundant RNAs from the bpRNA database [2] and then fine-tuned on 8,598 PDB RNAs released before January 2022. We performed rigorous benchmark tests on 279 RNAs from the widely used ArchiveII set and 27 newly released PDB RNAs. Both test sets were filtered to remove sequences with significant similarity to the training set, using a stringent E-value cutoff of 10 in a BLASTN [3] search. The results confirm that trRNA-SS consistently outperforms other recent deep learning and traditional methods on these benchmarks. More details about the benchmark results can be found in [4].

End-to-end version of trRosettaRNA. To improve both accuracy and speed, we extended trRosettaRNA to support the direct end-to-end prediction of the atomic coordinates. The first part of the updated pipeline largely resembles the original version, i.e., predicting 2D geometries using RNAformer stacks from the input MSA and SS. Subsequently, we adapted the key end-to-end components from AlphaFold2 [5] for RNA structure prediction, namely the invariant point attention (IPA)-based structure module and backbone frame representation. First, we incorporated SS information into the IPA module by multiplying it with the attention map, aiming to guide the 3D prediction with 2D information. Second, we represent each nucleotide with a rigid body frame C4’-C1’-N1/9 (N1 for pyrimidines, N9 for purines), corresponding to the N-CA-C frame in AlphaFold2, which is the primary objective to update in the structure module. Following RhoFold+ [6] (see its Supplementary Table 1), the final all-atom structure is reconstructed by mapping the ideal local coordinates of each atom to the global Cartesian coordinates, using the frame transitions derived from four predicted torsion angles. Similar to Alphafold2, the entire network is cycled four times using the recycling mechanism.

The updated trRosettaRNA network was trained on either 8,598 PDB RNAs released before January 2022 (for benchmarking on the TS39 set [4]) or 10,699 RNAs released before January 2024 (for participation in CASP16). Rigorous benchmark test on the TS39 set, which contains RNAs released after January 2022 and shares no significant sequence similarity to the training set (at a stringent E-value cutoff of 10), confirms that the updated trRosettaRNA outperforms its predecessor and other deep learning methods, including AlphaFold3. The blind test in CASP16 further confirms the robustness of trRosettaRNA as an automated approach [7, 8]. For more details about the TS39 benchmarking, please refer to [4].

Supplementary Table 1. Performance on the large CASP16 targets without detected templates. The RMSD values for predicted models are shown for the 11 targets with available experimental structures. The AF3-server and Yang-Server results are shown in "model 1/best model" format. "trRNA" refers to trRosettaRNA.

Target ID	Length	RMSD (Å)				
		AF3-server	Yang-Server	Default trRNA[#]	Best of traditional methods[*]	Best of all submissions
R1241[†]	480	8.2/6.8	8.0/7.0	12.7	38.5	2.3 (Vfold)
R1248	407	22.3/20.5	26.8/21.3	21.3	28.8	17.6 (OpenComplex_Server)
R1250	744	49.8/49.2	53.2/40.8	44.1	39.2	40.8 (Yang-Server)
R1251	833	61.0/60.7	53.2/53.2	57.6	53.8	38.9 (Diff)
R1252	520	57.8/43.7	42.2/35.4	40.1	43.3	33.6 (GuangzhouRNA-human)
R1253v1	574	49.9/43.3	42.0/42.0	29.2	46.1	38.0 (GuangzhouRNA-meta)
R1253v2	574	43.2/43.2	42.7/42.7	29.2	46.6	36.5 (NKRNA-s)
R1254	413	38.3/37.4	29.6/27.0[††]	31.0	40.1	24.6 (Diff)
R1283v1	580	21.3/19.4	38.7/29.9	39.2	37.1	18.4 (Bhattacharya)
R1285	577	8.2/8.1	8.6/8.6	28.0	29.3	6.9 (isyslab-hust)
R1286	526	48.8/48.4	64.3/45.4	39.4	50.7	31.3 (RNApolis)
Avg.	**566**	**37.2/34.7**	**37.2/32.2**	**33.8**	**41.2**	**26.3**

[#] Results in the "default trRosettaRNA" column were sourced from either the available Yang-Multimer Model 1 submission (for targets R1241, R1248, R1283v1, and R1285) or a local execution of the program (for all other targets).

[*] The "Best of traditional methods" column includes results from FARFAR2, SimRNA, RNAComposer, and 3dRNA. Vfold was excluded from this comparison due to its 300-nucleotide length limit.

[†] Templates are available for target R1241 but were missed by our automated template detection procedure during the competition.

[††] Yang-Server's submission for R1254 failed due to an unknown technical problem during the CASP16 season. As a result, we evaluated the models stored in our local file system.

Supplementary Table 2. Details of the 23 CASP16 RNA targets used in Fig. 2. This set includes all targets with a sequence length of less than 400 nucleotides or with available templates.

Target ID	Length	Experimental structure availability	Yang-Multimer submission availability
R1203	134	√	√
R1205	59	√	√
R1209	72	√	√
R1211	90	√	√
R1212	247	√	√
R1221s2	398	×	√
R1221s3	86	×	√
R1224s2	395	×	√
R1224s3	86	×	√
R1242	205	√	√
R1255	124	√	√
R1256	127	√	√
R1261	89	√	√
R1262	89	√	√
R1263	64	√	√
R1264	64	√	√
R1271	77	√	√
R1281	718	√	×
R1288	58	√	√
R1289	284	×	√
R1290	627	×	×
R1293	82	√	√
R1296	72	√	√

Supplementary Table 3. Clashscore comparison on the 11 large RNAs without detected templates. The lowest clashscore for each target is highlighted in bold.

Target ID	Length	Clashscore		
		AF3-server	**Yang-Server**	**Default trRosettaRNA**
R1241	480	15.0	13.6	**0.0**
R1248	407	30.8	**0.8**	**0.8**
R1250	744	68.7	**3.3**	22.2
R1251	833	35.3	**4.1**	8.7
R1252	520	34.6	8.9	**3.2**
R1253v1	574	53.1	**1.3**	4.0
R1253v2	574	48.2	**1.3**	5.9
R1254	413	36.3	\	**2.6**
R1283v1	580	24.5	**1.6**	5.3
R1285	577	97.6	**2.4**	19.3
R1286	526	18.1	**2.6**	4.0

Supplementary Table 4. Impact of MSA pruning on four RNAs with deep initial MSAs (>20,000 homologous sequences). Three different MSA processing strategies were compared: "Raw" refers to the full MSA generated by trRosettaRNA; "Top-20k" refers to the truncated MSA with the first 20,000 sequences retained; "Filtered" refers to the MSA filtered by HHfilter [9] to remove redundancy.

Target ID	**Length**	**MSA type**	**MSA depth**	**Memory (GB)**	**RMSD (Å)**
7UR5	90	Raw	34,518	15.4	4.2
		Top-20k	20,000	5.8	4.2
		Filtered	2,528	3.5	4.2
7VNV	76	Raw	632,631	Out of cluster memory	
		Top-20k	20,000	5.7	2.0
		Filtered	1,872	3.0	2.1
R1203	134	Raw	218,656	579.8	15.5
		Top-20k	20,000	5.8	15.0
		Filtered	1,502	4.8	15.4
R1271	77	Raw	130,097	205.9	3.8
		Top-20k	20,000	5.7	4.0
		Filtered	2,786	3.1	3.8

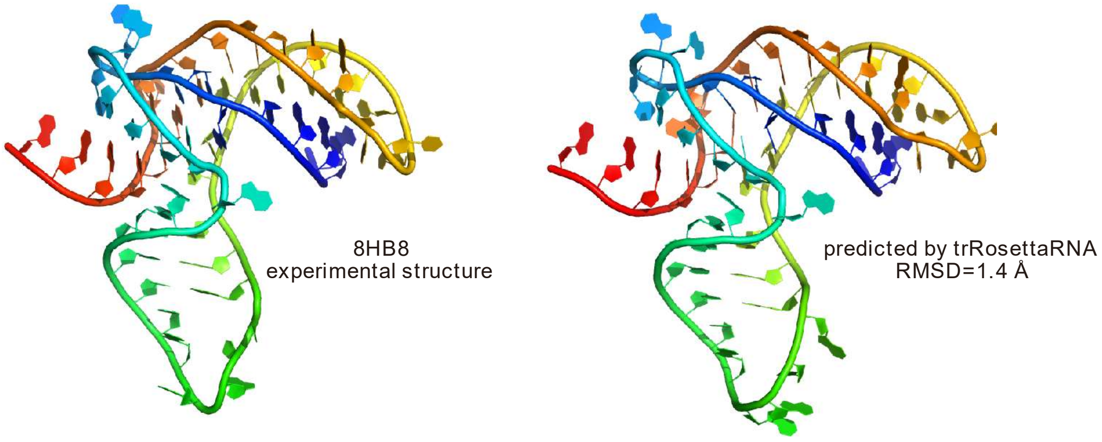
Supplementary Table 5. Performance on CASP16 RNA targets lacking both structural templates (best template TM-score$_{\mathrm{RNA}}$ < 0.45) and sufficient homologous sequences (N_{eff} < 130). This list is from the official CASP16 assessment report (Figure 1 in [8]). The AF3-server and Yang-Server results are shown in "model 1/best model" format. "trRNA" refers to trRosettaRNA.

Target ID	Length	RMSD (Å)				
		AF3-server	**Yang-Server**	**Default trRNA[#]**	**Best of traditional methods[*]**	**Best of all submissions**
R1205	59	10.1/10.1	12.6/12.6	11.5	19.7	7.5 (RNApolis)
R1209	72	9.8/9.3	12.4/11.6	14.7	14.5	7.8 (RNA_Dojo)
R1212	247	28.7/28.0	41.6/25.4	25.4	21.5	8.2 (RNApolis)
R1248	407	22.3/20.5	26.8/21.3	21.3	28.8	17.6 (OpenComplex-Server)
R1250	744	49.8/49.2	53.2/40.8	44.1	39.2	40.8 (Yang-Server)
R1251	833	61.0/60.7	53.2/53.2	57.6	53.8	38.8 (Diff)
R1252	520	57.8/43.7	42.2/35.4	40.1	43.3	33.6 (GuangzhouRNA-human)
R1254	413	38.3/37.4	29.6/27.0[†]	31.0	40.1	24.6 (Diff)
R1286	526	48.8/48.4	64.3/45.4	39.7	50.7	31.3 (RNApolis)
R1288	58	8.7/8.5	10.0/6.4	6.4	5.9	5.1 (Vfold)
R1296	72	9.8/8.3	10.5/8.5	10.0	12.9	3.1 (Vfold)
Avg.	**359**	**31.4/29.5**	**32.4/26.1**	**27.4**	**30.0**	**19.9**

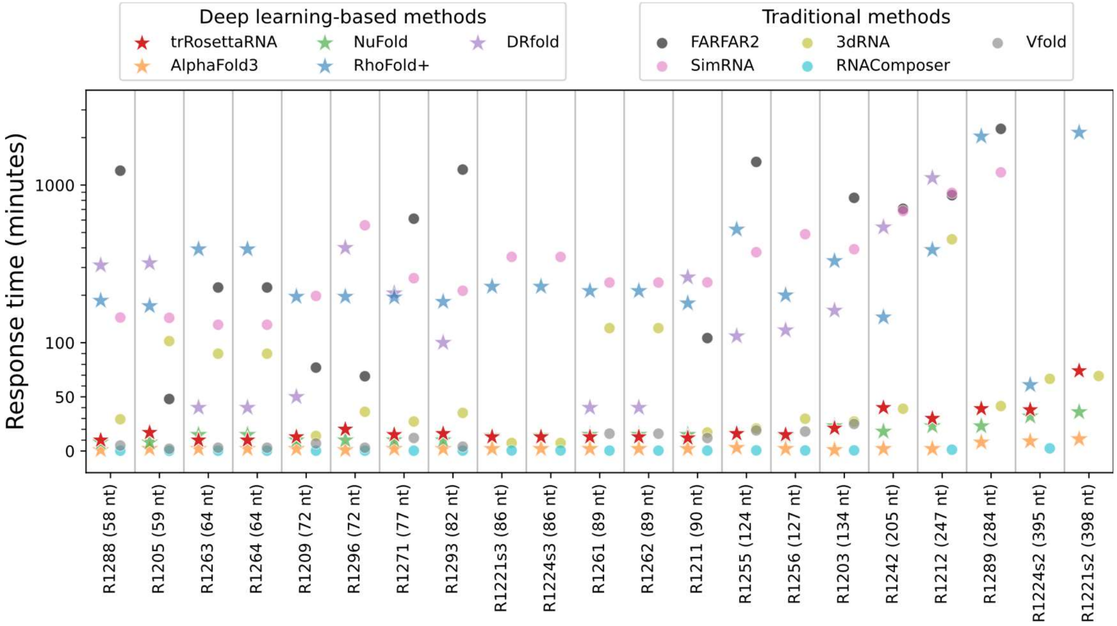
[#] Results in the "default trRosettaRNA" column were sourced from either the available Yang-Multimer Model 1 submission (for targets R1205, R1209, R1212, R1248, R1288, and R1296) or a local execution of the program (for all other targets).

[*] The "Best of traditional methods" column includes results from FARFAR2, SimRNA, Vfold RNAComposer, and 3dRNA.

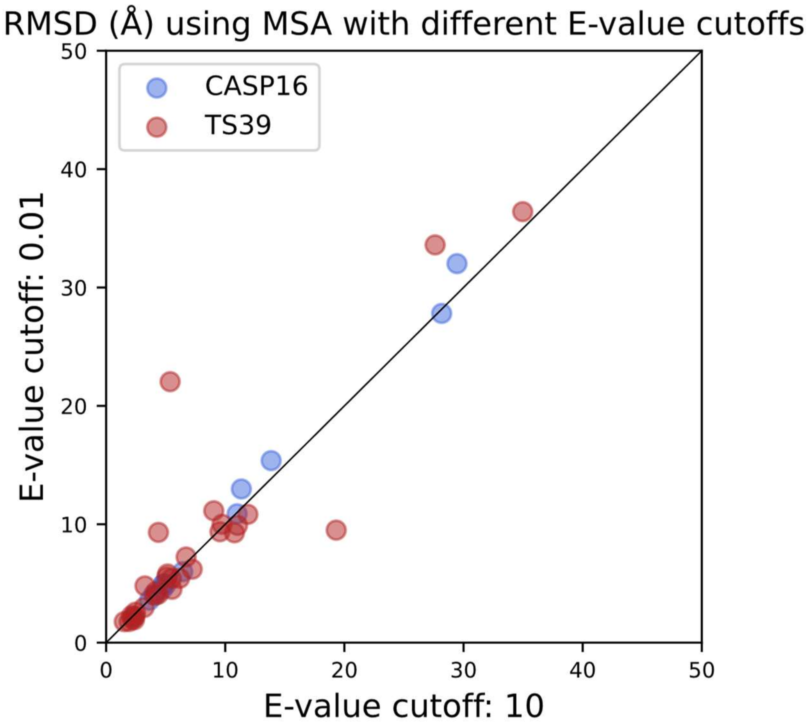
[†] Yang-Server's submission for R1254 failed due to an unknown technical problem during the CASP16 season. As a result, we evaluated the models stored in our local file system.



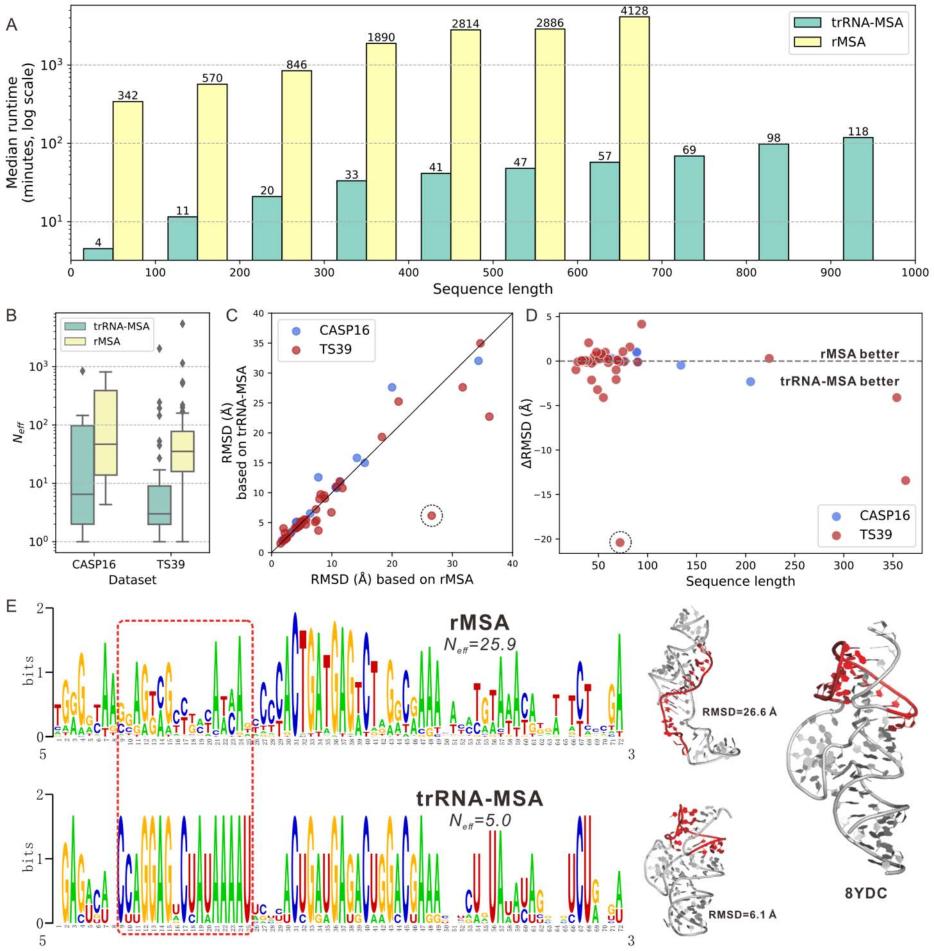
Supplementary Figure 1. Comparison between the experimental and predicted structures for an example RNA containing a triple helix (PDB ID: 8HB8).



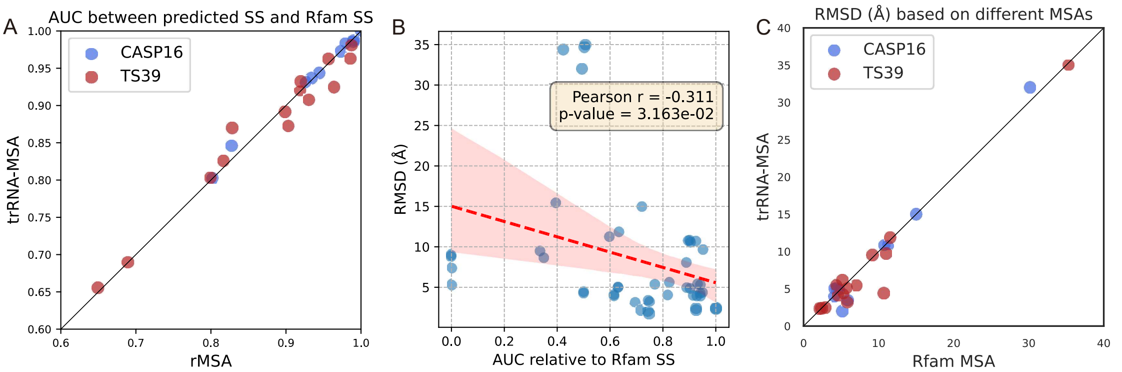
Supplementary Figure 2. Comparison of web server response time. This analysis was performed on 21 CASP16 targets with < 400 nucleotides from Supplementary Table 2 (sorted by sequence length). Stars represent deep learning-based methods, and circles represent traditional methods. Values over 100 are log-transformed for better visualization. To simulate a typical real-world use case, all servers were benchmarked using a single sequence as the sole input, allowing each to use its internal pipeline for MSA and/or secondary structure generation with all other parameters at their defaults. The reported response times include the queue time for each compared server. Note: RoseTTAFoldNA (no web server) and DeepFoldRNA (failed to return results within one month) were excluded from this analysis.



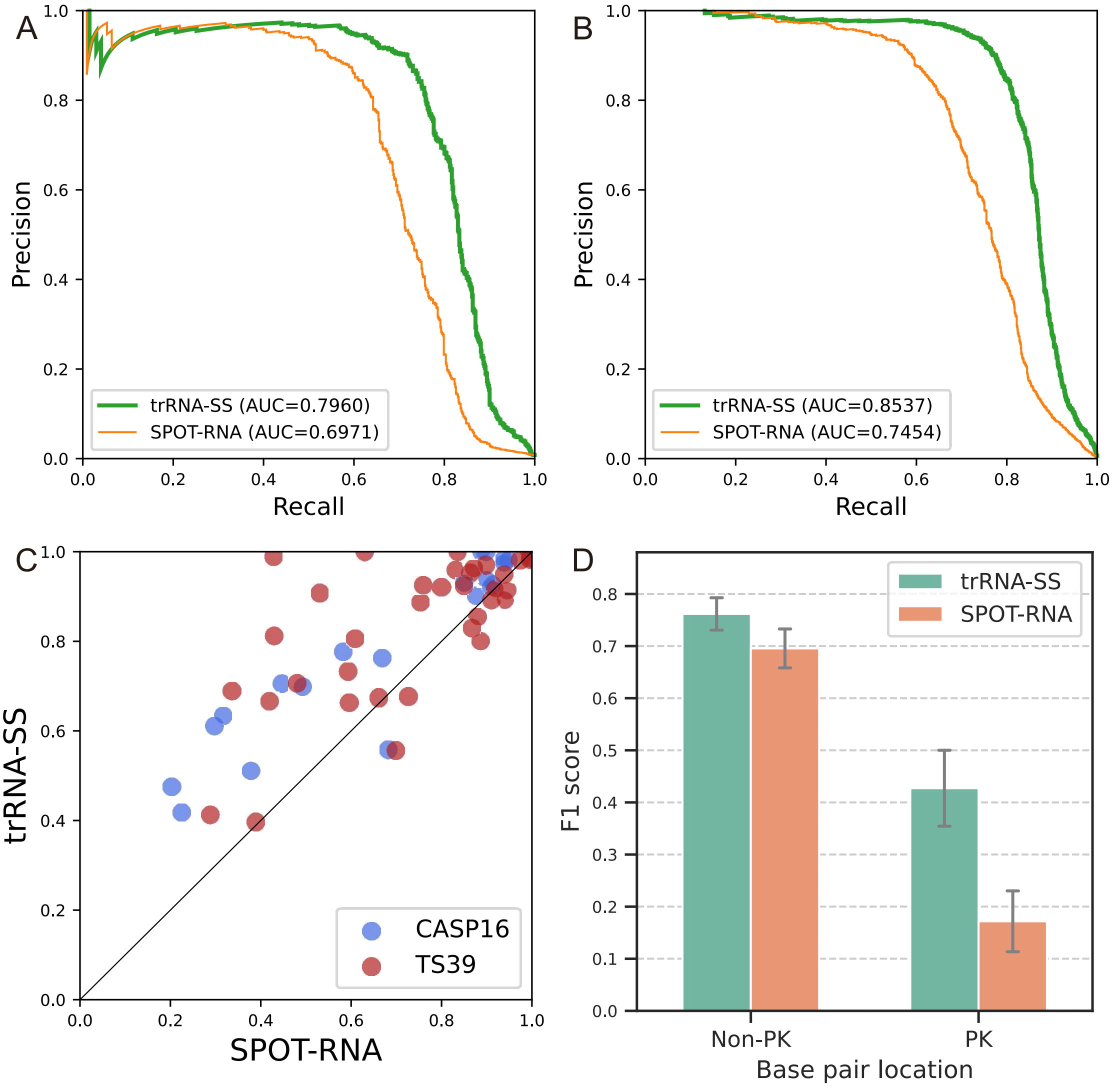
Supplementary Figure 3. Head-to-head comparison of model accuracy using MSAs generated with E-value cutoffs of 10 versus 0.01. The comparison is performed on the 16 CASP16 targets and 39 independent RNAs (TS39) from [4].



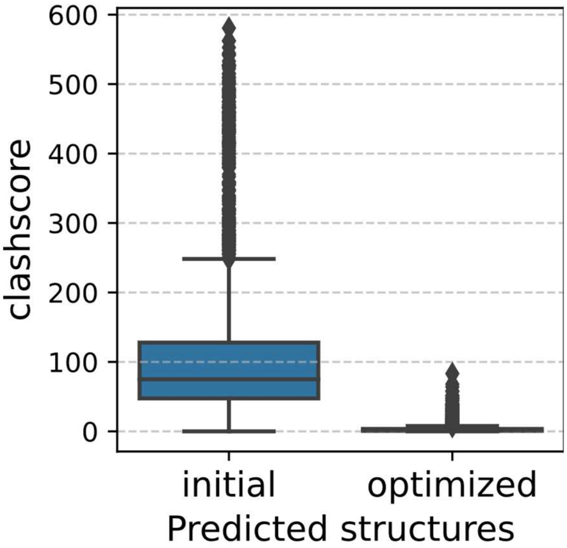
Supplementary Figure 4. Comparison between rMSA and MSA generated by the trRosettaRNA server (trRNA-MSA). (A) Comparison of the median runtimes for MSA search. Runtimes for trRNA-MSA were calculated based on the recent 3,000 server tasks. The rMSA runtime data were obtained from its supplementary materials [10]. The *y*-axis uses a logarithmic scale for better visualization. Numbers above the bars refer to the median runtime in minutes. (B) Box plot comparing the effective number of homologous sequences (N_{eff}, at 80% sequence identity cutoff) generated by rMSA and trRNA-MSA for the 16 CASP16 targets and 39 independent RNAs (TS39). (C) Head-to-head comparison between the 3D modeling accuracy using MSAs generated by rMSA versus trRNA-MSA on two benchmark sets. (D) The difference in model accuracy (ΔRMSD) as a function of sequence length. Positive values indicate rMSA is better; negative values indicate trRNA-MSA is better. (E) An example case (PDB ID: 8ydc), highlighted by circles in (C) and (D), where the MSA from trRNA-MSA leads to a more accurate structure prediction than rMSA. The key stem-loop responsible for the performance difference is highlighted by red boxes in the sequence logos and colored red in the 3D structures.



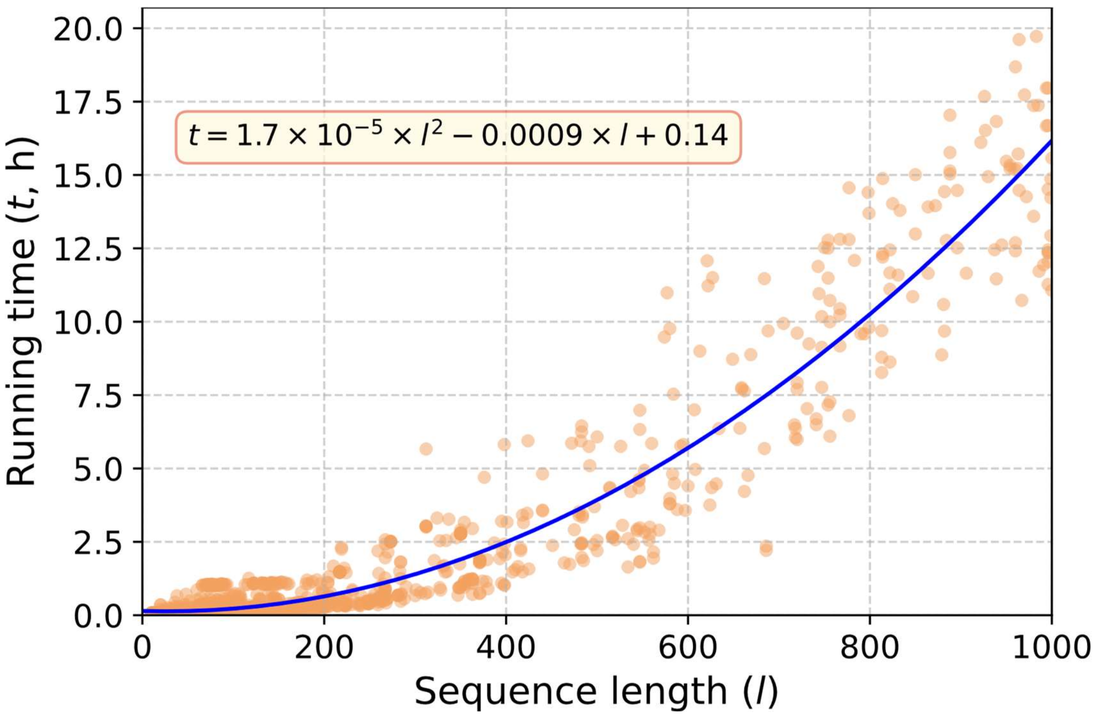
Supplementary Figure 5. Analysis of MSA quality against Rfam and the effect of E-value cutoff. (A) Head-to-head comparison of AUC scores for SSs predicted from trRNA-MSA and rMSA, relative to the Rfam consensus secondary structure, on 24 (10 from CASP16; 14 from TS39) targets with identified Rfam families. (B) Correlation between the final model RMSD and the AUC score relative to the Rfam consensus secondary structure. (C) Head-to-head comparison of model accuracy (RMSD) using the default trRNA-MSA versus the established Rfam family MSA. Note that for the above analyses, the consensus secondary structure and MSA from Rfam were aligned to the query sequence using the cmalign command in the Infernal package.



Supplementary Figure 6. Comparison between SPOT-RNA and SS from the trRosettaRNA server (trRNA-SS). (A-B) The precision-recall curves of SPOT-RNA and trRNA-SS on 16 CASP16 targets (A) and the TS39 set (B). (C) Head-to-head comparison of the area under the precision-recall curve (AUPRC) between SPOT-RNA and trRNA-SS on two sets. (D) Comparison of mean F1-scores for base pairs in pseudoknotted (PK) and non-pseudoknotted (Non-PK) regions, evaluated on 35 pseudoknotted RNAs from the two test sets (14 from CASP16 and 21 from TS39). PK regions were identified using bpRNA [2]. Error bars represent the standard deviation of the mean (SEM).



Supplementary Figure 7. Comparison of clashscore before and after structure optimization. Middle line: median (50th percentile). Box edges (bottom/top): first quartile (Q1, 25th percentile) and third quartile (Q3, 75th percentile). The box spans the interquartile range (IQR; middle 50% of data). Whiskers: extend to the farthest data points within 1.5 * IQR from the box. Individual points: outliers (beyond the 1.5 * IQR limit).



Supplementary Figure 8. Running time of trRosettaRNA server as a function of sequence length. Calculated based on the recent 3,000 tasks in November 2025.

References

1. Wang, W. *et al.* trRosettaRNA: automated prediction of RNA 3D structure with transformer network. *Nature Communications* **14**, 7266 (2023).
2. Danaee, P. *et al.* bpRNA: large-scale automated annotation and analysis of RNA secondary structure. *Nucleic Acids Research* **46**, 5381-5394 (2018).
3. Camacho, C. *et al.* BLAST+: architecture and applications. *BMC Bioinformatics* **10**, 421 (2009).
4. Wang, W., Peng, Z. & Yang, J. Predicting RNA 3D structure and conformers using a pre-trained secondary structure model and structure-aware attention. *bioRxiv*, 2025.2004.2009.647915 (2025).
5. Jumper, J. *et al.* Highly accurate protein structure prediction with AlphaFold. *Nature* **596**, 583-589 (2021).
6. Shen, T. *et al.* Accurate RNA 3D structure prediction using a language model-based deep learning approach. *Nature Methods* **21**, 2287-2298 (2024).
7. Wang, W., Luo, Y., Peng, Z. & Yang, J. Accurate Biomolecular Structure Prediction in CASP16 With Optimized Inputs to State-Of-The-Art Predictors. *Proteins: Structure, Function, and Bioinformatics* **n/a** (2025).
8. Kretsch, R.C. *et al.* Assessment of nucleic acid structure prediction in CASP16. *bioRxiv*, 2025.2005.2006.652459 (2025).
9. Steinegger, M. *et al.* HH-suite3 for fast remote homology detection and deep protein annotation. *BMC Bioinformatics* **20**, 473 (2019).
10. Zhang, C., Zhang, Y. & Pyle, A.M. rMSA: A Sequence Search and Alignment Algorithm to Improve RNA Structure Modeling. *Journal of Molecular Biology* **435**, 167904 (2023).