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Human Lin28 Forms a High-Affinity 1:1 Complex with the 106~363 Cluster miRNA miR-363

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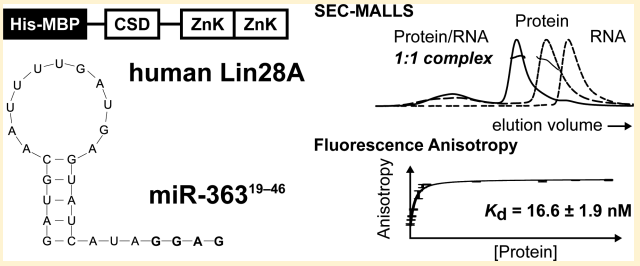
Supporting Information

ABSTRACT: Lin28A is a post-transcriptional regulator of gene expression that interacts with and negatively regulates the biogenesis of let-7 family miRNAs. Recent data suggested that Lin28A also binds the putative tumor suppressor miR-363, a member of the 106~363 cluster of miRNAs. Affinity for this miRNA and the stoichiometry of the protein−RNA complex are unknown. Characterization of human Lin28's interaction with RNA has been complicated by difficulties in producing stable RNA-free protein. We have engineered a maltose binding protein fusion with Lin28, which binds let-7 miRNA with a K_d of 54.1 ± 4.2 nM, in agreement with previous data on a murine homologue. We show that human Lin28A binds miR-363 with a 1:1 stoichiometry and with a similar, if not higher, affinity (K_d = 16.6 ± 1.9 nM). Further analysis suggests that the interaction of the N-terminal cold shock domain of Lin28A with RNA is salt-dependent, supporting a model in which the cold shock domain allows the protein to sample RNA substrates through transient electrostatic interactions.



Lin28 proteins are key post-transcriptional regulators of gene expression in higher eukaryotes.[1] They comprise two RNA binding domains: an N-terminal cold shock domain (CSD) and a C-terminal zinc knuckle (ZnK) domain with two tandem CCHC-type zinc knuckles. This unique domain combination allows specific interactions with mRNAs and microRNAs (miRNAs) that contain conserved GGAG/GGUG motifs.[1−6] Because of these interactions, Lin28 has been implicated in pluripotency,[7−9] development,[10−13] alternative splicing,[4] metabolism,[12,14] and cancer.[15−17] Identifying Lin28 targets and characterizing their interactions with Lin28 are therefore critical for understanding the molecular basis of Lin28-associated disorders.

The inhibition of let-7 family miRNA biogenesis by Lin28 has been widely studied. The binding of Lin28 to pre-let-7 in the cytoplasm prevents access of Dicer to its cleavage site. Further recruitment of terminal uridylyl transferase Zcchc11 results in the addition of a 3′ poly(U) tail,[6,18] targeting the precursor RNA for degradation by the Dis3L2 nuclease.[19] A crystal structure of murine Lin28a in complex with let-7 RNA showed that the CSD binds the loop/pre-element/preE region of the miRNA while the ZnK domain contacts the GGAG motif (illustrated in Figure 1A).[20] Analysis of *Xenopus* Lin28b showed that the protein bound 83-nucleotide *Xenopus*-pre-let-7f RNA with a K_d of 1.6 μM.[21] The same study showed that CSD remodels RNA structure to facilitate binding of the ZnK domain to the GGAG motif. More recent work with murine Lin28a suggested that the remodeling of RNA serves to expose additional sites for Lin28 binding, giving rise to 2:1 and 3:1 protein−RNA complexes, where effectively the protein shields pre-let-7 from Dicer.[22] An overall affinity of 0.13 nM was reported for such binding of Lin28 to a 46-nucleotide let-7g substrate.[23] Affinities of 1.7 and 0.29 nM were observed for 14-nucleotide GAGG- and GGAG-containing segments of this substrate, respectively.[22]

Among miRNAs outside of the let-7 family, several contain a 3′-GGAG motif and are targets of Lin28-dependent uridylation by Zcchc11.[6] In contrast, miR-363 of the 106~363 cluster, which also has this motif (Figure 1B) and a binding partner of Lin28, is not subjected to uridylation by Zcchc11, suggesting that its interaction with Lin28 is part of a previously uncharacterized regulatory pathway. Recently, a direct interaction between *Xenopus* Lin28 and the terminal loop of the precursor *Xenopus*-miR-363 has been described.[24] Contrary to what was observed for let-7 RNAs, knockdown of Lin28 in morphant embryos led to a decrease in mature miR-363 levels, suggesting an alternate function for Lin28 as a positive regulator of miR-363.

Previous studies of the interaction of human Lin28 with RNA were undermined by the unstable nature of this protein in the absence of bound nucleic acid. Here, we report a new

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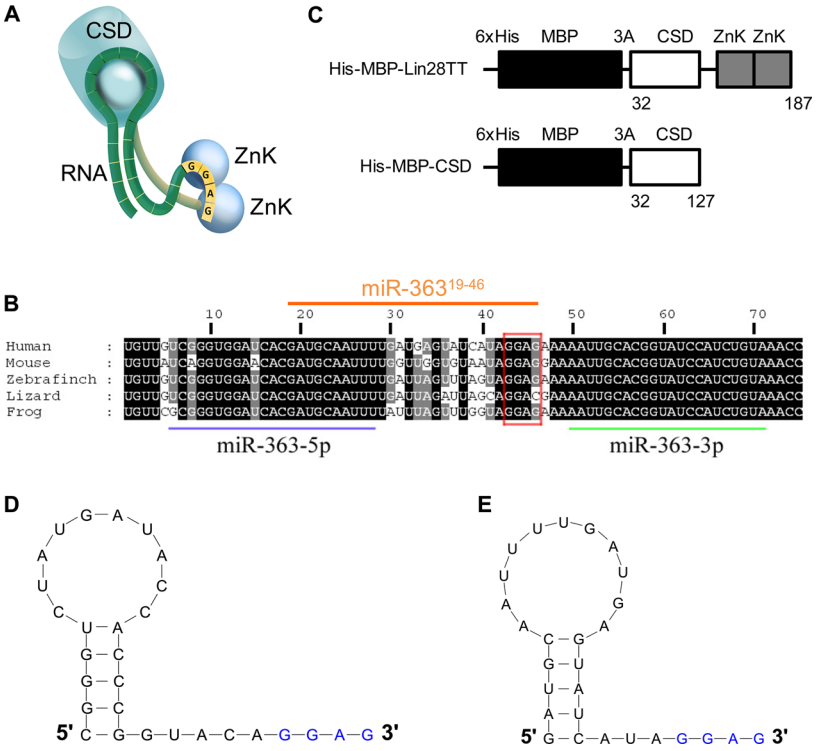

Figure 1. Lin28 and miRNA. (A) Architecture of the complex of Lin28 with miRNA.[20] (B) Alignment of pre-miR-363 sequences from several vertebrates. The conserved GGAG motif is highlighted (red box), and the region of the sequence corresponding to the miR-363$^{19-46}$ segment used in this study is colored orange; segments of full-length mature miR-363 are colored blue (5′) and green (3′). (C) Schematic of Lin28 constructs used in this study. Secondary structures of (D) let-7g$^{29-57}$ and (E) miR-363$^{19-46}$, predicted by MFOLD.[27]

strategy for producing stable, RNA-free, recombinant human Lin28. We show that the human protein binds both let-7g and miR-363 with high affinity in a 1:1 stoichiometry. We further show that this complex is resistant to changes in ionic strength. In contrast, the CSD on its own binds in a manner that is highly dependent on ionic strength. These data suggest that the electrostatic properties of CSD play a major role in helping Lin28 search for RNA targets in the transcriptome.

EXPERIMENTAL PROCEDURES

Protein Production. The plasmid encoding the His-MBP-Lin28TT fusion protein (Figure 1C) was produced from the pETFF_2 plasmid provided by the York Technology Facility. The sequence encoding residues 32−187 of human Lin28A (NCBI accession number NP_078950.1) was amplified by polymerase chain reaction (PCR) from a synthetic, codon-optimized template (GeneArt). The pETFF_2 vector was linearized by PCR and purified by agarose gel electrophoresis. The Lin28 sequence was then inserted into the pETFF_2 vector using the In-Fusion ligation system (Clontech) and the product transformed into *Escherichia coli*.

The plasmid encoding the His-MBP-Lin28TT protein was transformed into the Rosetta2 (DE3) *E. coli* expression strain. Cells were grown in LB medium supplemented with 50 μM $ZnCl_2$ to an OD_{600} of 0.6. Expression was then induced by the addition of 1 mM isopropyl β-D-1-thiogalactopyranoside, and cells were grown overnight at 16 °C. Cells were harvested, resuspended on ice in 50 mM Tris-HCl (pH 7.5), 150 mM NaCl, 2 mM β-mercaptoethanol, 10 μM $ZnCl_2$, and 20 mM imidazole, and lysed by sonication. The lysate was applied to a Zn^{2+}-charged 5 mL HisTrap column (GE Healthcare) at 4 °C. The column was then washed for 16 h (flow rate of 0.1 mL/min) at 4 °C, with a solution containing 50 mM MES (pH 6.0), 1 M NaCl, 2 mM β-mercaptoethanol, 10 μM $ZnCl_2$, and 20 mM imidazole to remove nucleic acid contaminants. Bound proteins were eluted using 50 mM MES (pH 6.0), 1 M NaCl, 2 mM β-mercaptoethanol, 10 μM $ZnCl_2$, and 500 mM imidazole. The eluted protein was applied to a S200 10/300 gel filtration column (GE Healthcare) in a solution containing 10 mM MES (pH 6.0), 1 M NaCl, 2 mM β-mercaptoethanol, and 10 μM $ZnCl_2$. Fractions containing the Lin28 fusion protein were concentrated and dialyzed against a solution containing 10 mM Tris-HCl (pH 7.5), 150 mM NaCl, 2 mM β-mercaptoethanol, and 10 μM $ZnCl_2$ before being flash-frozen in liquid nitrogen for storage.

RNA Constructs. Unlabeled and 5′-fluorescein-labeled RNA corresponding to human let-7g and miR-363 (Figure 1D,E) were synthesized by Dharmacon. A cytosine was introduced to the 5′ end of the let-7g RNA for additional stability from base pairing. A similar approach was taken in previous studies of murine let-7g RNA.[20]

SEC−MALLS. A Biosep SEC S3000 column (Phenomenex) was pre-equilibrated with 20 mM Tris (pH 7.5) and 250 mM NaCl buffer and connected to a Dawn Helios II 18-angle light-scattering detector (Wyatt Technology). Lin28 fusion protein samples were diluted to 2 mg/mL (34 and 38 μM for His-MBP-Lin28TT and His-MBP-CSD, respectively) in buffer or buffer with equimolar amounts of RNA oligonucleotide. The eluting species were detected by measuring the UV absorbance at 280 nm; the concentration of the species was determined using an Optilab rEX refractometer (Wyatt Technology), and a refractive index increment of 0.185 mL/g was used for calculation of the molecular weight in the ASTRA V software.

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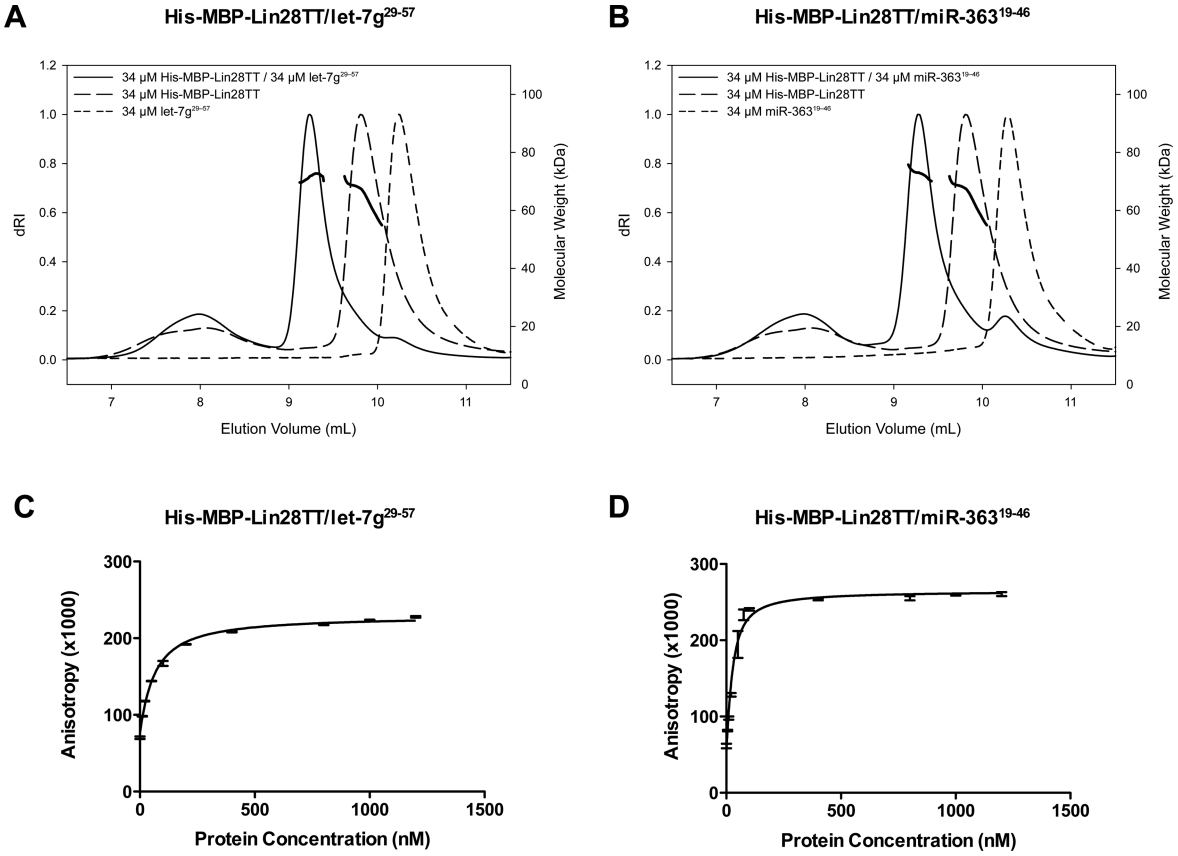

Figure 2. Analysis of the interaction of Lin28 with RNA. SEC−MALLS analysis of protein, RNA, and the protein−RNA complex with elution profiles shown for (A) let-7g$^{29-57}$ and (B) miR-363$^{19-46}$. Fluorescence anisotropy analysis of the interaction of Lin28 with 5′-fluorescein-labeled (C) let-7g$^{29-57}$ and (D) miR-363$^{19-46}$ in 20 mM Tris-HCl (pH 7.5), 100 mM NaCl, 10 mM β-mercaptoethanol, 50 μM $ZnCl_2$, and 0.01% (v/v) Tween 20.

Weight-average molecular weight values and the associated error of the fit are reported.

Fluorescence Anisotropy. Titrations were performed using increasing concentrations of protein and 20 nM 5′-fluorescein-labeled RNA in 200 μL final volumes, in triplicate. The sample buffer contained 20 mM Tris-HCl (pH 7.5), 50−750 mM NaCl, 10 mM β-mercaptoethanol, 50 μM $ZnCl_2$, and 0.01% (v/v) Tween 20. Fluorescence readings were taken in a black flat-bottom 96-well plate (Nunc) at 25 °C in a BMG POLARstar Optima plate reader with the detector gain set using an initial measurement of 20 nM free fluorescein in buffer. Dissociation constants for His-MBP-Lin28TT−RNA interactions were determined by fitting the following equation in Prism (GraphPad):

$$y = A_{min} + (A_{max} - A_{min}) \times \frac{c + x + K_d - \sqrt{(c + x + K_d)^2 - 4xc}}{2c}$$

where x is the concentration of protein in nanomolar, y is the anisotropy (×1000), A_{min} is the anisotropy of free labeled RNA, A_{max} is the maximal anisotropy, c is the total concentration of labeled RNA (set to 20 nM), and K_d is the dissociation constant.

RESULTS

Human Lin28 Fused to MBP Can Be Purified as a Soluble, Nucleic Acid-Free Preparation. Initial attempts to produce nucleic acid-free human Lin28A as a His_6 fusion failed, as the protein quickly became lost upon removal of the nucleic acid with NaCl treatment (Figure S1). To improve solubility and stability, constructs were designed in which Lin28A (residues 32−187, Lin28TT) or the CSD on its own (residues 32−127) was fused with His-tagged maltose binding protein (His-MBP) via a three-alanine peptide linker (Figure 1C). A long salt wash was included in the purification protocol to remove nucleic acid contaminants, which otherwise caused all protein to elute as a high-molecular weight protein/nucleic acid mixture during size exclusion chromatography (Figure S2).

Human Lin28 Forms 1:1 Complexes with let-7g and miR-363. The His-MBP-Lin28TT fusion protein eluted in two steps during size exclusion chromatography: a sharp peak at 9.8 mL, corresponding to monomeric protein, with a weight-average molecular weight of 65 ± 4 kDa, determined by MALLS (theoretical mass of 59.5 kDa), and a broad peak in the void volume, indicating aggregation and accounting for ∼24% of the eluting protein mass, calculated on the basis of refractive index measurements.

Injecting equimolar amounts of His-MBP-Lin28TT and let-7g$^{29-57}$ RNA resulted in an earlier eluting peak relative to free monomeric protein and RNA (Figure 2A). An average molecular weight of 72 ± 1 kDa was determined, comparable to the theoretical mass of 68.4 kDa for a 1:1 protein−RNA complex.

The interaction of Lin28 with miR-363 was investigated using a 28-nucleotide RNA segment, which includes the

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characteristic stem loop and the conserved GGAG motif [miR-363$^{19-46}$ (Figure 1A,E)]. As with let-7g, an earlier eluting peak was observed for the protein/RNA mixture relative to free monomeric protein and RNA, with an observed molecular weight of 73 ± 2 kDa (Figure 2B). This agrees with the 68.8 kDa mass calculated for a 1:1 protein−RNA complex.

Lin28 Binds let-7g and miR-363 with High Affinity. The affinities of human Lin28 for let-7 RNA and miR-363 were subsequently measured. The fusion protein was titrated against a constant concentration of 5′-fluorescein-labeled let-7g$^{29-57}$ and miR-363$^{19-46}$, and changes in fluorescence anisotropy were measured (Figure 2C,D). Equilibrium dissociation constants of 54.1 ± 4.2 and 16.6 ± 1.9 nM were deduced, respectively, under a 1:1 interaction model. No interaction was observed between the His-MBP tag and RNA (Figure S3). These data suggest that Lin28 binds let-7 RNA and miR-363 with comparable affinities.

Lin28 CSD Forms Higher-Order Species with let-7g and miR-363 RNA. To elucidate the role of the CSD in RNA binding, a His-MBP-CSD fusion protein was produced and its interactions with let-7g$^{29-57}$ and miR-363$^{19-46}$ were studied. A significant peak in the void volume during size exclusion chromatography indicated that His-MBP-CSD has a strong tendency to aggregate, with approximately 76% of the eluting protein present in this peak (Figure 3). A peak corresponding to the 52 kDa monomeric protein could still be observed, with an experimental molecular weight of 52 ± 1 kDa. When the complex was mixed with let-7g and miR-363, a new peak corresponding to the complex was observed with average molecular weights of 76 ± 1 and 72 ± 2 kDa, respectively (Figure 3). These values are between the expected molecular weights of 62 and 113 kDa for 1:1 and 2:1 protein−RNA complexes, respectively. These data could be the result of protein aggregating while it is bound to RNA. Alternatively, they may indicate that the CSD does not bind RNA in a strict 1:1 manner, in agreement with previous reports on murine Lin28 forming high-order complexes with RNA.[22] In contrast with the relatively monodisperse 1:1 binding behavior exhibited by the full-length protein, it can be proposed that the ZnK domain facilitates the formation of stable 1:1 complexes.

Lin28−miR363 Complexes Are Insensitive to Salt Concentration. To determine if electrostatic forces play any role in the Lin28−miR-363$^{19-46}$ interaction, the fluorescence anisotropy experiments were repeated under different ionic strength conditions. As the exact nature of the His-MBP-CSD−RNA complexes is not known, an appropriate model for data fitting could not be determined. However, the general trend in the affinity of the interaction can be seen qualitatively by comparing the anisotropy at different ionic strengths. The data show that for the two-domain His-MBP-Lin28TT protein, the affinity of the interaction remained relatively constant under all conditions (Figure 4A and Table S1). Conversely, the His-MBP-CSD−miR-363$^{19-46}$ interaction became weaker as the ionic strength of the buffer increased (Figure 4B), so much so that no binding was observed at 750 mM NaCl. These data show that unlike the case for the two-domain protein, the interaction of the CSD with RNA is sensitive to ionic strength. This implies that electrostatic interactions have a far greater role when the ZnK domain is not present.

DISCUSSION

Lin28 Interacts with miR-363. The miR-363 miRNA was identified as a potential binding partner of Lin28, as the 3′-

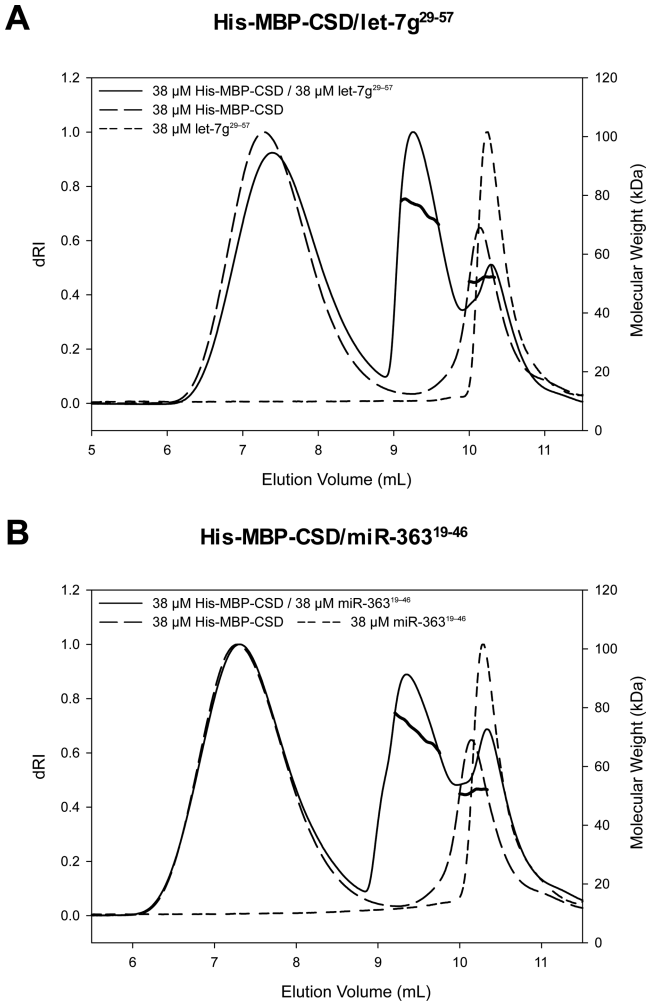

Figure 3. SEC−MALLS analysis of the interaction of His-MBP-CSD with RNA. Elution profiles are shown for protein, RNA, and protein−RNA complexes for (A) let-7g$^{29-57}$ and (B) miR-363$^{19-46}$.

GGAG motif present in this sequence is highly conserved in land-based vertebrates. miR-363 is a member of the 106~363 miRNA cluster, a cluster paralogous to the 17−92 miRNA oncomir cluster.[28,29] Recent reports have identified miR-363 as a putative tumor suppressor. In neuroblastoma cells, miR-363 expression inhibits colony formation, growth, invasion, and metastasis through downregulation of the MYO1D and ADAM15 oncogenes.[30] miR-363 expression has been also linked with better prognosis and decreased metastatic potential in head and neck squamous cell carcinoma due to its targeting of podoplanin.[31] Expression of miR-363 also inhibits the growth of a cell line derived from a NK-cell lymphoma.[32] Given that both Lin28 and miR-363 are both implicated in the development of cancer, understanding the nature of Lin28−miR-363 interaction is of potential medical interest.

Previously reported K_d values for the interaction between Lin28 proteins and let-7 RNAs[20−23,25,26] display a large degree of variation, with differences of >4 orders of magnitude. The reasons for such a large discrepancy are likely complex and could range from sample preparation to buffer conditions to the length and structure of the oligonucleotide tested.

Here, we show that the miR-363 RNA segment containing the characteristic stem loop followed by the GGAG motif forms a relatively stable complex with a human Lin28A fusion protein,

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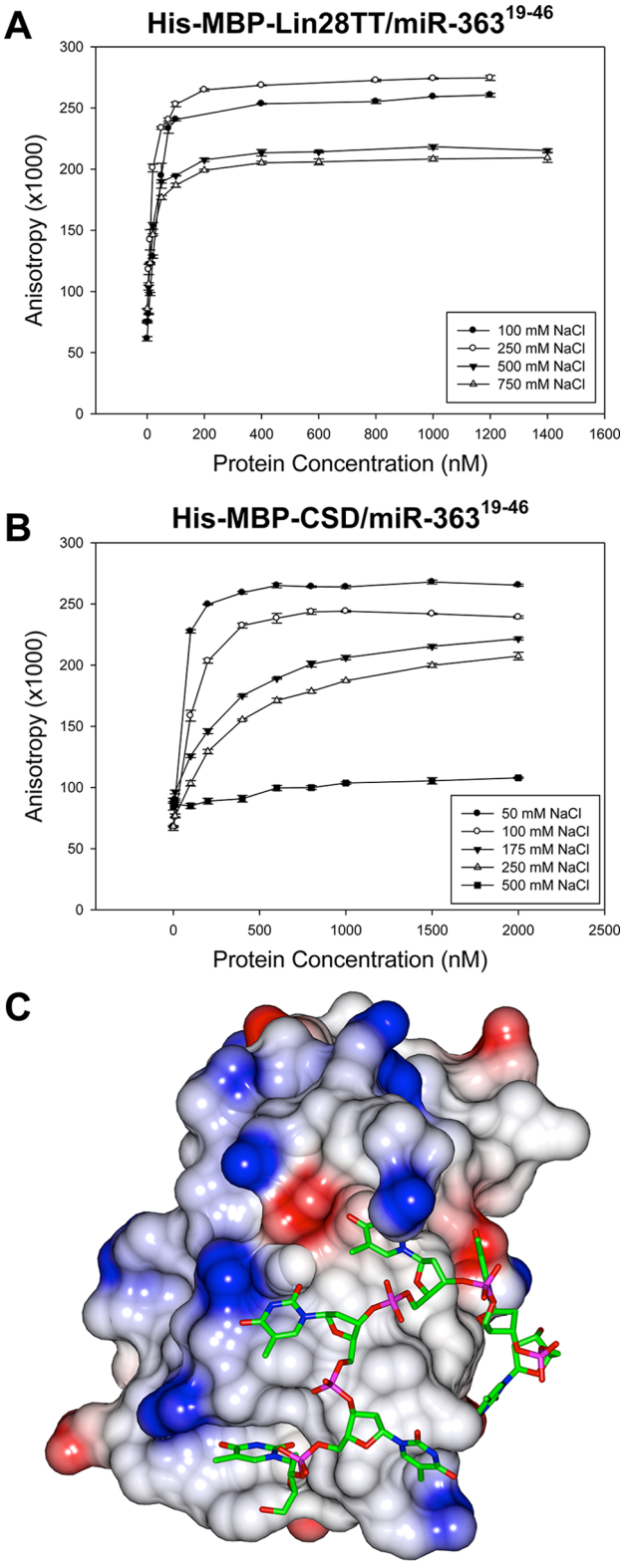

Figure 4. Effect of ionic strength on the interaction of Lin28 with miR-363. Fluorescence anisotropy experiments were conducted using fluorescein-labeled miR-363$^{19-46}$ at different ionic strengths with increasing concentrations of (A) His-MBP-Lin28TT or (B) His-MBP-CSD. (C) Model of the complex of human CSD with nucleic acid based on atomic structures of human Lin28b CSD (Protein Data Bank entry 4A4I) and the *Xenopus* Lin28b CSD–DNA complex (Protein Data Bank entry 4A75). The electrostatic surface potential for the human CSD, from −1 V (red) to +1 V (blue).

with a K_d of 16.6 ± 1.9 nM under the described conditions (Figure 2D). SEC–MALLS analysis indicates a 1:1 protein:RNA stoichiometry in the complex (Figure 2B). We also observe a 1:1 interaction with an equivalent segment of let-7g RNA (Figure 2A), in agreement with an earlier observation of a 1:1 complex made with an RNA oligonucleotide of similar length and secondary structure, derived from the terminal loop of *Mmu*let-7d.[20] Additionally, the K_d of 54.1 ± 4.2 nM of this interaction is comparable to the affinity of His-MBP-Lin28TT for the miR-363 RNA segment (Figure 2D). The data therefore indicate that Lin28 binds miR-363 and let-7 miRNAs in a similar manner.

This finding is of interest as the Lin28–miR-363 complex was shown to promote very little uridylation by Zcchc11 compared to that by let-7a-1.[6] In addition, the evidence of a direct interaction between amphibian Lin28 and miR-363, as well as the observation that knockdown of Lin28 results in decreased mature miR-363 levels, implies the alternative function of Lin28 as a positive regulator of miRNA biogenesis.[24] The results presented here show the similarities between the binding modes of let-7g and miR-363. Previously, it has been proposed that a change in the conformation of the 3′ terminus of the let-7g hairpin caused by Lin28 binding may facilitate the recruitment of the TUTase responsible for let-7g uridylation.[20] Differences in the conformations of bound miR-363 and let-7g would not be detectable by the methods employed here but could account for the differences in the biological outcomes of Lin28 binding through the recruitment of different downstream effectors. Further studies identifying factors that may interact with and influence binding of Lin28 to miRNA, as well as structural information about such assemblies, may be useful for improving our understanding of this system.

Determinants of Lin28:RNA Stoichiometry. A recent study demonstrated that Lin28 binds the let-7g 46-nucleotide stem loop segment in a stepwise manner, with up to three protein molecules per RNA.[22] Interactions were mediated by three RNA segments, containing an exposed loop of the let-7g stem loop or either the 5′-GGAG-3′ motif or its reverse (5′-GAGG-3′). The let-7g$^{29-57}$ oligonucleotide used here is shorter (29 nucleotides) and contains only the 3′-GGAG motif. Likewise, the miR-363$^{19-46}$ and *Mmu*-let-7d RNA oligonucleotides contain only one GGAG motif, at the 3′ end. It is therefore possible that the stoichiometry of a Lin28–RNA complex is determined by (1) the number of GGAG motifs present in the RNA, which determine the specific attachment to RNA, and (2) the length of the RNA, which determines the number of CSD molecules that can be accommodated on exposed single-stranded RNA regions.

Lin28 CSD Guides RNA Binding via Electrostatic Attraction. The structures of murine Lin28A in complex with let-7 family miRNA sequences,[20] and of the *Xenopus* Lin28B CSD domain,[21] show binding of the CSD to single-stranded oligonucleotides through stacking interactions between the RNA bases and aromatic side chains on the CSD surface. In tandem, the ZnK domain binds the GGAG motif through a hydrogen-bonding network, with a stacking interaction formed between the side chain of Y140 and the bases of the final A and G of the motif.[20]

The sensitivity of the interaction of His-MBP-CSD with RNA to ionic strength (Figure 4B) implies that electrostatic forces play an equally important role in RNA binding. Examination of the CSD's electrostatic surface reveals clear areas of positive charge surrounding the nucleic acid binding

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site (Figure 4C). Apart from Lys95 (Lys92 in the human CSD), the phosphate groups seen in the structure are not directly contacted by these areas of positive charge. However, a major difference between the bacterial cold shock protein homologues and the Lin28 CSD is the addition of two extra lysine residues to strand β4, which results in a more basic binding platform.[21] It is therefore possible that these areas of positive charge could fulfill a key role in attracting and guiding RNA to the binding site, facilitating the formation of base-specific hydrophobic and hydrogen-bond interactions as observed in crystal structures.

In conclusion, we propose that Lin28 uses its CSD to sample the transcriptome through transient electrostatic associations, similar to how DNA binding proteins locate their target sites through facilitated diffusion, by "sliding" and "hopping".[33−36] If Lin28 were to display a similar behavior, it would increase the likelihood of ZnK binding to the short GGAG motif for stable complex formation. Depending on the structure and sequence of the RNA, melting and the association of further Lin28 molecules could then occur. Such a model may also be relevant in light of recent work showing Lin28 can also bind to DNA and influence gene expression through the recruitment of epigenetic modification factors.[37] Future work will therefore need to elucidate Lin28's interaction with both the genome and transcriptome.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.biochem.6b00682.

Protein stability following removal of the nucleic acid via salt treatment (Figure S1), purification of His-MBP-Lin28TT (Figure S2), fluorescence anisotropy analysis of His-MBP with RNA (Figure S3), and equilibrium dissociation constants of the His-MBP-Lin28TT−miR-363[19−46] interaction at different NaCl concentrations, as measured by fluorescence anisotropy (Table S1) (PDF)

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

CSD, cold shock domain; ZnK, zinc knuckle; miRNA, microRNA; *Xenopus*, *Xenopus tropicalis*; *Mmu*, *Mus musculus*; MBP, maltose binding protein; His-MBP-Lin28TT, His-MBP-Lin28 with truncated termini; SEC−MALLS, size exclusion chromatography coupled with multiangle laser light scattering.

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