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Poly(A)-binding proteins are functionally distinct and have essential roles during vertebrate development

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Translational control of many mRNAs in developing metazoan embryos is achieved by alterations in their poly(A) tail length. A family of cytoplasmic poly(A)-binding proteins (PABPs) bind the poly(A) tail and can regulate mRNA translation and stability. However, despite the extensive biochemical characterization of one family member (PABP1), surprisingly little is known about their in vivo roles or mechanisms of action. Because no information is available in vertebrates, we address their biological roles, establishing that each of the cytoplasmic PABPs conserved in Xenopus laevis [PABP1, embryonic PABP (ePABP), and PABP4] is essential for normal development. Morpholino-mediated knockdown of PABP1 or ePABP causes both anterior and posterior phenotypes and embryonic lethality. In contrast, depletion of PABP4 results mainly in anterior defects and lethality at later stages. Unexpectedly, cross-rescue experiments reveal that neither ePABP nor PABP4 can fully rescue PABP1 depletion, establishing that PABPs have distinct functions. Comparative analysis of the uncharacterized PABP4 with PABP1 and ePABP shows that it shares a mechanistically conserved core role in promoting global translation. Consistent with this analysis, each morphant displays protein synthesis defects, suggesting that their roles in mRNA-specific translational regulation and/or mRNA decay, rather than global translation, underlie the functional differences between PABPs. Domain-swap experiments reveal that the basis of the functional specificity is complex, involving multiple domains of PABPs, and is conferred, at least in part, by protein–protein interactions.

global translational control | mRNA-specific translational control | RNA-binding protein | translation initiation | end-to-end complexes

Early vertebrate development is directed by maternally transcribed mRNAs (1) that are deadenylated upon their exit from the nucleus and are stored in a translationally inactive state (2). During specific developmental stages, subsets of mRNAs are readenylated in a highly regulated process known as cytoplasmic polyadenylation (3, 4) concomitant with their translational activation. Although they have been best studied during early development, dynamic changes in poly(A) tail length also occur in other cell types. The function of the poly(A) tail in stimulating translation is mediated by the binding of the cytoplasmic poly(A)-binding protein (PABP) family of proteins, which are structurally and functionally distinct from nuclear PABPs (5, 6). Although vertebrates express multiple cytoplasmic PABPs, which contain a conserved domain organization, most studies have focused on the prototypical member PABP1 [also known as PABP, cytoplasmic 1 (PABPC1)]. The N terminus of PABP1 contains four nonidentical RNA recognition motifs (RRMs) that mediate both RNA and protein interactions. The C terminus comprises a highly variable proline-rich region that mediates PABP–PABP interactions important for oligomerization along the poly(A) tail and the PABP C-terminal domain (PABC) [also known as the MLLE domain] responsible for several protein–protein interactions (5, 6).

Biochemical studies suggest that metazoan PABP1 stimulates translation initiation by simultaneously binding the poly(A) tail and interacting with other translation factors located at the 5′ UTR, including eukaryotic initiation factor (eIF)4G and poly(A)-binding protein interacting protein 1 (PAIP1) (7–9). These interactions mediate the circularization of the mRNA, promoting recruitment of the small ribosomal subunit (40S) and perhaps recycling of translation initiation factors and terminating ribosomes (10). Furthermore, PABP1 has a largely uncharacterized effect on large ribosomal subunit (60S) recruitment and participates in translation termination via binding to eukaryotic release factor 3 (eRF3) (5, 6, 11). In addition to this core role in translation, PABP1 also functions in mRNA turnover and nonsense-mediated decay (12, 13). Moreover, it is emerging that PABP1 has a variety of mRNA-specific roles, including translational activation and mRNA-mediated repression (5, 14). This multifunctionality is not fully understood but appears to be conferred by the ability of PABP1 to interact with key factors. The other PABPs remain largely uncharacterized, although the molecular functions of embryonic PABP (ePABP, also known as ePAB or PABP1-like) have been partially described (15–18).

Given the key role of PABP1 in regulating posttranscriptional gene expression and its extensive functional characterization, it is surprising that relatively little is known about the biological roles of PABP proteins. Deletion of the single poly(A)-binding protein (PABI) in Saccharomyces cerevisiae, which serves both nuclear and cytoplasmic functions, is lethal (19), although in Schiza saccharomyces pombe spermatogenesis is normal (20). In Drosophila melanogaster, deletion/reduction of dPABP or its deregulated expression leads to embryonic lethality/male sterility or neurophysiological defects, respectively (21, 22). Caenorhabditis elegans encodes two cytoplasmic PABPs, and mutations in tsab-1 cause defects in the germline and affect longevity (23, 24). However, an absence of studies precludes any conclusion regarding the essential nature of PABPs in vertebrates.

During Xenopus laevis development, in which the effects of cytoplasmic polyadenylation have been studied extensively, the expression patterns of the two identified PABPs are distinctive: ePABP protein is abundant during oogenes and early embryogenesis and is absent later in development. PABP1 protein is reciprocally expressed, being present at low levels during oogenesis and early embryogenesis and gradually increasing after the resumption of zygotic transcription at the midblastula transition.


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Development.

Fig. S4

16 embryos injected with control (Ctr) or PABP1-A (PABP1) morpholino PABP1 depletion causes multiple developmental defects and em-

and 20 (asterisk). (Additional photographs are no. 19
and ± May 10, 2011

Fig. S4

Fig. S2

∼ D B | ± ± 10 ng of PABP1 rescue mRNA, using antibodies speci-

ment defects (Fig. 1

protein expression (Fig. 1

When coinjected with PABP1 morpholino, it rescued PABP1

of morpholino, this mRNA did not cause defects (Fig. S3), excluding off-target effects. Embryos injected with the ePABP mRNA in the absence of morpholino did not display developmental defects (Fig. S3A). Importantly, an alternative ePABP-specific morpholino generated similar phenotypes (Fig. S4C), further showing the morphological and movement defects to be specific. These data provide insight into the biological role of ePABP, establishing that, like PABP1, it is essential for vertebrate development.

Fig. 1. PABP1 depletion causes multiple developmental defects and embryonic lethality. (A) Western blot analysis of whole-cell extracts from stage 14–16 embryos injected with control (Ctr) or PABP1-A (PABP1) morpholino (Mo) ± 10 ng of PABP1 rescue mRNA, using antibodies specific for PABP1 and ePABP. (B) Representative photographs of stage 29/30 embryos injected with control or PABP1-A morpholino ± 10 ng of PABP1 rescue mRNA. PABP1 morphants show abnormal development of anterior (closed arrow) and posterior (open arrow) structures, spinal curvature (arrowhead), and developmental arrest at stage 18–20 (asterisk). (Additional photographs are shown in Fig. S2.) (C) Percentages of control, PABP1 morpholino, and PABP1 rescue embryos (stage 29/30) displaying the indicated phenotypes. Morphological defects include spinal curvature; abnormal development of eye, cement gland, tail, and fin; ventral edema; absence of posterior development; and developmental arrest at stage 18–20. Data represent the average of nine (PABP1 morpholino) or six (PABP1 rescue) independent experiments, with ~1,200 or 900 embryos per experimental point, respectively.

Results

PABP1 and ePABP Are Essential for X. laevis Development. To analyze the phenotypic consequences of PABP deficiency in vertebrates, we injected X. laevis embryos with morpholino antisense oligonucleotides that blocked the translation of specific PABPs (Fig. S1). Strikingly, 100% of embryos injected with a PABP1-specific morpholino, which depleted PABP1 levels by >90% in vivo (Fig. L4), were defective, exhibiting a wide variety of anterior and posterior defects (Fig. 1 B and C). Specific morphological defects became apparent at stage 25, and all embryos died by stage 30/31. As is typical of morpholino-mediated knockdown, a range of phenotypes was observed: Phenotypes at stage 29/30 included abnormal development of eyes, cement gland, tail, and fin, different degrees of body axis curvature, and defective posterior elongation, with single embryos often having multiple defects (Fig. 1B and Fig. S2A). In some cases development was arrested at stage 18–20. The few embryos that appeared morphologically normal had movement defects, because they did not respond when prodded (Fig. 1C). In contrast, only 10 to 25% of embryos injected with control morpholino exhibited defects, including spine bifida and early death, representing nonspecific effects. Importantly, injection of another morpholino directed against a different region of PABP1 mRNA resulted in very similar phenotypic effects (Fig. S2). To probe further the specificity of the PABP1 phenotypes, a modified PABP1 mRNA that could not be recognized by the morpholino (morpholino-resistant) was injected at different concentrations. In the absence of morpholino, this mRNA did not cause defects (Fig. S3A). When coinjected with PABP1 morpholino, it rescued PABP1 protein expression (Fig. L4) and the morphological and movement defects (Fig. 1 B and C and Fig. S2A), with normal embryos observed at ~80% of the frequency seen with control morpholino. Taken together, these data establish that normal vertebrate embryogenesis depends on PABP1 expression.

Embryos injected with a morpholino that blocks ePABP translation in vitro and in vivo (Figs. S1B and S4A) showed a similar range of morphological and movement defects, although death occurred later, by stage 35. This finding was perhaps surprising, because ePABP is the predominant PABP in early em-

bryos, but may result from the higher levels of maternal ePABP (15, 16). ePABP defects were present in both anterior and pos-
terior structures and also were fully penetrant (Fig. 2 A and B and Fig. S4B). Efficient phenotypic rescue was achieved by coinjecting a morpholino-resistant ePABP mRNA (Fig. 2 A and B and Fig. S4B), excluding off-target effects. Embryos injected with the ePABP mRNA in the absence of morpholino did not display developmental defects (Fig. S3A). Importantly, an alternative ePABP-specific morpholino generated similar phenotypes (Fig. S4C), further showing the morphological and movement defects to be specific. These data provide insight into the biological role of ePABP, establishing that, like PABP1, it is essential for vertebrate development.

To gain insight into the mechanism underlying the PABP1 and ePABP phenotypes, we analyzed the effect of their depletion on global protein synthesis in embryos. PABP1 and ePABP morphants both showed a significant reduction in global protein synthesis, of 40% and 25%, respectively (Fig. 2 C and D), with the latter perhaps reflecting the higher levels of maternal ePABP (15, 16).

PABP4 Depletion Causes Anterior Defects and Embryonic Lethality. Bioinformatic analysis identified a PABP mRNA in X. laevis encoding a protein that is most closely related to mammalian PABP4 (Fig. S5 A and B). This newly identified PABP4 maintains the same domain organization as PABP1 (5) and exhibits high homology to human PABP4 (81% identity) and X. laevis PABP1 (75% identity). PABP4 mRNA, like PABP1, was detected in a wide variety of adult tissues (Fig. S5C), consistent with studies in mammals (25). PABP4 mRNA is expressed in early oocytes, decreases during later oogenesis, and reappears from stage 7/8 embryos (Fig. S5D) at the onset of zygotic transcription, when ePABP is still the predominant PABP protein.

We investigated the developmental role of this newly identified PABP by injecting a PABP4-specific morpholino (Fig. S1C). Interestingly, morphological defects were observed only after
In contrast to PABP1 and ePABP, PABP4 depletion appeared to be associated mainly with anterior defects, leading us to inject the morpholino into a single presumptive anterior or posterior cell at the four- to eight-cell stage, targeting only one side of the embryo. At stage 35–37 PABP4 depletion only caused defects following injection into an anterior blastomere; 70% of embryos showed abnormal eye development on the injected side (Fig. 3 D and F), indicating that formation of anterior structures is more sensitive to PABP4 depletion. In contrast, ePABP knockdown caused defective phenotypes after either anterior or posterior injection (Fig. 3 E and F), consistent with the results shown in Fig. 24.

Because PABP4 depletion led to the most distinct phenotypes, and this vertebrate-specific PABP remains largely uncharacterized, we investigated whether differences in its putative core function in translation contribute to its developmental requirement. To assess PABP4 function in vivo, the polyome profiles of PABP4-deficient embryos were analyzed, revealing a clear reduction in polysome peaks compared with control embryos (Fig. 3G), which reflects a significant decrease in global protein synthesis. Thus, defects in translation appear to be an important facet of the PABP4 phenotype. Consistent with this result, PABP4 was found to associate with polysomal and nonpolysomal fractions when expressed in oocytes, reminiscent of ePABP (Fig. S64). To explore the extent of the mechanistic similarity between PABP4 and PABP1/ePABP, we directly examined its quantitative ability to stimulate translation and its interaction with protein partners. Tethered function analysis in intact oocytes (9, 17) revealed that PABP4 stimulates the translation of mRNAs to a level equivalent to PABP1 and ePABP (Fig. S6 B–D). Moreover, we found that PABP4 binds poly(A) RNA (Fig S74) consistent with observations in mammals (25, 26), interacts with translation factors known to be protein partners of X. laevis PABP1 and ePABP (9, 17, 27), and engages in PABP–PABP interactions (Fig. S7 C–E), suggesting that PABP4 may bind mRNAs cooperatively with other PABPs. Thus, both the ability of PABP4 to stimulate translation and its mode of action seem to be conserved, revealing that differences in this core function do not appear to underlie the unique developmental requirement for this PABP.

**PABP1, ePABP, and PABP4 Have Distinct Functions.** Conservation of their core role in translation does not preclude the possibility that other distinct molecular functions and/or differences in their temporospatial expression contribute to the different phenotypes associated with PABP1, ePABP, or PABP4 depletion. Thus, cross-rescue experiments were undertaken with mRNAs containing identical generic 5' and 3' UTRs to negate differences in their embogenesis. Injection of mRNAs encoding either PABP1-FLAG or PABP4-FLAG into PABP1 morphants resulted in similar levels of ectopic PABP proteins (Fig. S3C), as expected. PABP1-FLAG mediated efficient rescue, reducing the PABP1-specific phenotypes (morphological and movement) from 91% to 28% of embryos (Fig. 4A and Fig. S84). PABP4-FLAG expression did not rescue the specific phenotypes to the same extent, because they were reduced only from 91% to 52% (Fig. 4A). Strikingly, cross-rescue of PABP1 with an ePABP mRNA only reduced the percentage of specific phenotypes from 84% to 42%, whereas PABP1 self-rescue reduced these specific phenotypes to 16% (Fig. 4B and Fig. S8B). Thus, these data establish that neither PABP4 nor ePABP can completely substitute for PABP1 during development, providing evidence that metazoan members of this family have nonredundant as well as overlapping molecular functions.

**Multiple Determinants Underlie PABP Specificity.** Our data reveal the existence of functional differences between PABP family members (Fig. 4), which are not linked to their function in global translation (Figs. 2 C and D and 3G and Figs. S6 and S7). The C-terminal region is the most diverse among PABPs, leading us to hypothesize that it may be responsible for these differences. To address this hypothesis, domain-swap experiments were undertaken between the RRM and C-terminal regions of PABP1.
and ePABP, which share 83% and 56% identity, respectively. First, the C terminus of PABP1 was appended to the RRM region of ePABP (eRRM/1Ct) and was coinjected with the PABP1 morpholino. Interestingly, rescue with eRRM/1Ct reduced PABP1-specific phenotypes from 89% to 28%, compared with a reduction from 89% to 43% with wild-type ePABP (Fig. 5A), showing that substitution of the PABP1 C terminus results in a more efficient rescue. However, this rescue was less efficient than wild-type PABP1, although Western blotting showed that the hybrid protein was expressed similarly in embryos (Fig. 5B). Importantly, the reciprocal rescue of PABP1 phenotypes using a construct in which the ePABP C terminus was appended to the RRM of PABP1 (1RRM/eCt) also gave an intermediate level of cross rescue (Fig. 5C and D). Thus, our data reveal that multiple regions underlie the unique requirement for PABP1.

**Discussion**

By providing phenotypic studies of PABPs in vertebrate development, we have uncovered essential but distinct functional roles for all three members of the *X. laevis* PABP family. These results significantly extend the previous analysis of PABP1 in yeast and invertebrates (19–24). In each case, developmental defects were accompanied by a significant loss of protein synthesis, establishing the role of metazoan PABPs in protein synthesis in vivo and showing that a decrease in overall translation contributes to the phenotypes. However, given the pleiotropic nature of PABP1, it is likely that defects in other aspects of posttranscriptional regulation (5, 12–14) also contribute to the phenotypes. Interestingly, injection of PABP mRNA in non-depleted embryos did not result in phenotypic consequences, suggesting that overexpression is tolerated.

Altered PABP levels or differences in their temporo-spatial expression may contribute to the observed phenotypes. However, cross-rescue experiments revealed that neither PABP4 nor ePABP, even when similarly expressed, can substitute completely for PABP1, because the percentage of defective phenotypes obtained is approximately two and three times greater, respectively, than with the PABP1 self-rescue. These results strongly indicate...
that differential molecular functions also must contribute to the requiremnt for multiple PABPs during development, which is intriguing, given the high degree of amino acid similarity, especially between PABP1 and PABP4. Thus, our results identify the existence of biologically relevant differences between the functions of individual PABP family members in metazoa.

Importantly, mechanistic analysis of PABP function provides insight into the basis of these differences. We establish that PABP1, ePABP, and PABP4 each has an important role in determining overall translation rates in vivo, and SDS/PAGE analysis of [35S]methionine-labeled extracts from embryos suggest that synthesis of a wide range of proteins is affected (Fig. S9), confirming an effect on global translation. These global defects are consistent with our finding that PABP4 can bind poly(A) and stimulate translation similarly to PABP1 and ePABP, sharing interactions with basal translation factors. The evolutionary conservation of PABP4 suggests that this ability may be maintained in other species. Thus, all three PABPs appear to play indistinguishable rather than distinct roles in global translation, excluding this as a mechanism to explain the specificity. This situation differs from the eIF4A family in which one member (eIF4AIII) appears to have an alternative function in post-transcriptional regulation (28, 29).

Since their ability to promote global translation does not vary significantly, their distinct functions must be related to other aspects of posttranscriptional control in which their roles are less well characterized. Cross-rescue experiments swapping the less conserved C-terminal region of PABP1 and ePABP, although unable to formally exclude subtle or cell type-specific differences in PABP stability, revealed that multiple regions contribute to PABP specificity. Because the C-terminal region mediates interactions with proteins but not with RNA (Fig. S10A), our results strongly suggest that PABP-specific protein interactions with partners other than basal translation factors (which interact with all three) play a role in the requirement for individual PABPs. The high conservation of the PABC domain suggests that differential protein interactions may be mediated by the proline-rich region, which is highly variable and predicted to be alternatively spliced in mammals, providing great scope for PABP-specific protein–protein interactions. It is tempting to speculate that PABP-specific protein partners may be involved in mRNA-specific regulation, as misregulation of even a single essential mRNA could be sufficient to cause lethality. In this regard it is interesting to note that translational activation by mRNA-specific binding proteins that directly recruit PABP through C-terminal interactions has been described in X. laevis (30). However, the few characterized interactions mediated by this region do not appear to be PABP specific (Fig. S10A and C); thus exhaustive identification of the PABP interactome is required.

Our data also, surprisingly, show that the relatively conserved RRM1–4 region is important for PABP specificity. This region interacts with both proteins and RNA, including, in other species, proteins that are involved in mRNA-specific regulation (31–33). Any differential RNA binding probably involves elements other than the poly(A) tail, because each of the PABPs binds poly(A) efficiently (Fig. S7A and B). Thus, poly(A)-independent recruitment of individual PABPs to specific mRNAs, via RNA or proteins, may provide additional mechanisms for regulating mRNAs that are stored during development with short poly(A) tails.

In conclusion, our investigation provides insight into the distinct roles of vertebrate PABPs and in so doing argues against the hypothesis that members of this family are functionally redundant. These unexpected differences provide an explanation for developmental switching between PABPs (15, 16) and the presence of multiple PABPs within many mammalian cell types (34) and emphasize the importance of dissecting the roles of individual family members in whole organisms. The approach

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described here provides a powerful in vivo tool for future work aimed at understanding the challenging and intriguing issues of PABP function and specificity.

Methods

Plasmid construction and supporting procedures are described in SI Methods. Animal experiments were performed under license and in accordance with the Animals in Scientific Procedures Act (1986).

The following translation-blocking morpholino antisense oligonucleotides, modified with 3′ carboxyfluorescein, were used (Gene Tools): PABP1-A: 5′ (UTR) CTTACCTCT CTCTATTCC GGATT; PABP1-B: (AUG) GGAGTGCCGG GGGAGTT; ePABP-A: (5′ UT) GAGTTGGCCCC TCAGGCGCTA AACTC; ePABP-B: (AUG) CGGCGCGGTG TTGATCTTG; PABP4: 5′ (UTR) CACGAGAA TTAGGGGAG GCTAA; Control: CCTCTACCTCT CAGTTAAC AT ATT.

Approximately 7 females of morpholino and/or 1–10 ng of in vitro transcribed, capped, and polyadenylated mRNA were injected into both blastomeres in X. laevis embryos at the two-cell stage. Injections into single anterior or posterior blastomeres were performed with 3 females of morpholino at the four- to eight-cell stage. Injected embryos were selected by fluorescence and allowed to progress for phenotype analysis. Embryos were staged according to Nieuwkoop and Faber (35). For photography, embryos were fixed in 0.1 M 3-(N-Morpholino)propanesulfonic acid (pH 7.4), 2 mM EGTA, 1 mM MgSO4, and 3.7% formaldehyde and were washed and stored in 100% ethanol.

Western Blot Analysis

Embryos were homogenized mechanically in TE buffer (10 mM Tris-HCl, pH 8, 1 mM EDTA, pH 7.4) supplemented with 0.5% sodium deoxycholate and 150 μg/mL cycloheximide and 20 mM EDTA. Cleared supernatants were layered onto a 10–50% sucrose gradient over a 60% cushion in basic lysis buffer and centrifuged for 2 h at 247,000 × g (38,000 rpm) using a TH-641 rotor (Sorval). Fractions were collected using a density gradient fractionation system (Teledyne Isco). Proteins were extracted from fractions by 10% TCA precipitation before Western analysis.

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