Processing-Body Movement in Arabidopsis Depends on an Interaction between Myosins and DECAPPING PROTEIN1

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Processing (P)-bodies are cytoplasmic RNA protein aggregates responsible for the storage, degradation, and quality control of translationally repressed messenger RNAs in eukaryotic cells. In mammals, P-body-related RNA and protein exchanges are actomyosin dependent, whereas P-body movement requires intact microtubules. In contrast, in plants, P-body motility is actin based. In this study, we show the direct interaction of the P-body core component DECAPPING PROTEIN1 (DCP1) with the tails of different unconventional myosins in Arabidopsis (Arabidopsis thaliana). By performing coexpression studies with AtDCP1, dominant-negative myosin fragments, as well as functional full-length myosin XI-K, the association of P-bodies and myosins was analyzed in detail. Finally, the combination of mutant analyses and characterization of P-body movement patterns showed that myosin XI-K is essential for fast and directed P-body transport. Together, our data indicate that P-body movement in plants is governed by myosin XI members through direct binding to AtDCP1 rather than through an adapter protein, as known for membrane-coated organelles. Interspecies and intraspecies interaction approaches with mammalian and yeast protein homologs suggest that this mechanism is evolutionarily conserved among eukaryotes.

**Newly synthesized mRNAs are processed and transported from the nucleus into the cytoplasm. Their subsequent fate depends on a regulatory balance between cytoplasmic translation and mRNA degradation. Both processes are modulated by mRNA-binding proteins, which influence the translational efficiency, stability, and localization of mRNA molecules. Over the last decade, it became apparent that messenger ribonucleoproteins that are translationally repressed and associated with the cytoplasmic 5' to 3' decapping machinery tend to assemble into a newly discovered class of highly dynamic mRNA granules, termed processing (P)-bodies (Sheth and Parker, 2003; Anderson and Kedersha, 2006; Parker and Sheth, 2007; Franks and Lykke-Andersen, 2008). P-bodies were initially identified as discrete cytoplasmic punctae to which the mouse 5' to 3' exonuclease localizes (Bashkirov et al., 1997). Since then, they have been established as major cytoplasmic sites for the storage of translationally repressed mRNAs, 5' to 3' mRNA degradation, quality control, and microRNA-dependent gene silencing (Dunckley and Parker, 1999; Sheth and Parker, 2003; Cougot et al., 2004; Sen and Blau, 2005).

Although their complete composition is still not known, a set of proteins related to these different functions has been identified and shown to colocalize with each other in these cytoplasmic foci (Ingelfinger et al., 2002; van Dijk et al., 2002; Sheth and Parker, 2003; Eulalio et al., 2007; Parker and Sheth, 2007). P-bodies are commonly described as highly mobile and dynamic structures (Yang et al., 2004; Aizer et al., 2008; Loschi et al., 2009). In Drosophila melanogaster and mammals, they show a microtubule-dependent pattern of motility (Aizer et al., 2008; Loschi et al., 2009), which is inhibited by drugs interfering with the microtubule cytoskeleton (Aizer et al., 2008). Actin, by contrast, is important for the delivery of RNA and P-body components to P-bodies and for their assembly. This is suggested by the colocalization of mammalian myosin Va with the P-body-associated protein eIF4E (for Eukaryotic Translation Initiation Factor4E) and further by the reduction of P-body number and transport of eIF4E to P-bodies when expressing dominant-negative myosin Va fragments (Lindsay and McCaffrey, 2011). An association of myosins with P-bodies was also reported in yeast. In yeast (Saccharomyces cerevisiae), Myo2p was successfully used to immunoprecipitate complex ribonucleoprotein particles, including hundreds of mRNAs and some P-body components, such as DECAPPING PROTEIN1 (Dcp1p), SM-LIKE PROTEIN1, DNA TOPOISOMERASE 2-ASSOCIATED PROTEIN1, DExD/H-BOX HELICASE1, and EXORIBONUCLEASE1 (Chang et al., 2008).

In plants, P-body movement appears to be based on the actin cytoskeleton (Hamada et al., 2012), although...
myosins have not been implicated in P-body movement. In Arabidopsis (Arabidopsis thaliana), the myosin family contains 17 proteins (Reddy and Day, 2001; Peremyslov et al., 2011), which are grouped into two classes, XI and VIII. Members of the class VIII myosins are associated with endosomal structures, the endoplasmic reticulum, and plasmodesmata (Avisar et al., 2008a; Golomb et al., 2008; Sattarzadeh et al., 2008). The 13 class XI myosins show a domain structure that is similar to those of fungi and animal myosin V proteins. They are composed of an N-terminal motor domain, for both actin association as well as ATP hydrolysis (Kinkema et al., 1994; Tominaga et al., 2003), an internal neck domain, comprising a stretch of six calmodulin-binding IQ motifs (Kinkema and Schiefelbein, 1994), and the C-terminal tail region, which contains a coiled-coil domain of variable extent and a bipartite globular cargo-binding domain (Pashkova et al., 2006; Li and Nebenführ, 2007). The Arabidopsis XI myosins have been implicated in the movement of various membranous organelles and vesicles (for review, see Sparkes, 2010, 2011). Colocalization studies and the analysis of movement in myosin mutants revealed that plant XI myosins are involved in the rapid trafficking of Golgi stacks, mitochondria, and peroxisomes (Avisar et al., 2008b, 2009; Peremyslov et al., 2008, 2010; Prokhnevsky et al., 2008), the long-distance transport of endomembrane vesicles (Peremyslov et al., 2012), plant-specific transport vesicles (Peremyslov et al., 2013), motility of plastids (Natesan et al., 2009; Sattarzadeh et al., 2009), as well as endoplasmic reticulum flow (Peremyslov et al., 2010; Ueda et al., 2010) and remodeling (Sparkes et al., 2009).

In the light of recent data available for the mammalian and yeast systems, myosins appear to be good candidates to also mediate the movement of membranless RNA granules, such as P-bodies. The molecular basis linking P-bodies to the actin cytoskeleton is not known in any system. In this study, we demonstrate that the P-body core component DECAPPING PROTEIN1 (DCP1) physically interacts with myosins in mammals, yeast, and Arabidopsis and also in interspecies experiments. In support of a direct interaction between myosins and P-bodies, Arabidopsis DCP1 (AtDCP1) colocalizes with the full-size myosin XI-K. Overexpression of dominant-negative myosin tail domains inhibited P-body movement efficiently. The analysis of the respective mutants revealed that in two xi-k alleles, P-body movement was almost completely abolished. This defective motility was efficiently restored in triple myosin knockout plants expressing full-size myosin XI-K. Taken together, these data demonstrate that P-body movement is governed by unconventional myosins and that their anchoring to myosins occurs by direct binding to a core component rather than by connecting to specific adapter proteins, as known for eukaryotic organelle transport.

RESULTS

AtDCP1 Interacts with Myosin XI Tails

In this study, we focused our analysis on four class XI myosins, XI-1, XI-2, XI-I, and XI-K, which were previously identified to be entirely responsible for the movement of different organelles during sporophyte development in Arabidopsis (Peremyslov et al., 2010). As myosins bind their cargos through their tail domains, these have been widely and successfully used to study myosin-cargo interactions (Pashkova et al., 2005; Li and Nebenführ, 2007; Reisen and Hanson, 2007; Golomb et al., 2008; Avisar et al., 2009; Sattarzadeh et al., 2009; Wang et al., 2012; Peremyslov et al., 2013). Therefore, this strategy was also adopted in our study. The tail domains of XI-1, XI-2, XI-I, and XI-K, lacking their motor and neck domains, were fused to the GAL4 Binding Domain (GAL4-BD), and a GAL4 Activation Domain (GAL4-AD) was fused to AtDCP1. Strikingly, we found an interaction between the prey protein GAL4-AD-AtDCP1 and all four myosin tails investigated as bait constructs (Fig. 1A). As AtDCP1 exhibits strong autoactivation as a GAL4-BD fusion protein, we could not test the reciprocal combinations. This first interaction assay was confirmed by two independent approaches. We performed in vitro coprecipitation assays using bacterially expressed proteins. The Maltose Binding Protein (MBP)-tagged myosin tails were bound to amylase resin and incubated with the cell lysates of Escherichia coli expressing glutathione S-transferase (GST)- and His6-tagged AtDCP1 fusion protein. Coprecipitation of GST-His6-tagged AtDCP1 with the XI-1, XI-2, XI-I, and XI-K tails was confirmed by anti-His antibody staining on a western blot (Fig. 1B; Supplemental Fig. S1A). To provide independent support for these interactions, we used fluorescence resonance energy transfer (FRET) assays that have been successfully applied before for the tail of MyoVb (Roland et al., 2007). As FRET measurements with mobile proteins are error prone, we developed an in vitro FRET assay to measure FRET efficiencies photometrically. AtDCP1-cyan fluorescent protein (CFP) and -yellow fluorescent protein (YFP) fusions of the myosin tails were separately expressed in Arabidopsis cell suspension cultures. Lysates of transfected cells were combined using the YFP and CFP fluorescence intensities to adjust the same ratios between the donor protein AtDCP1-CFP and different YFP-labeled myosin tails as acceptor proteins. FRET was measured photometrically by the acceptor photobleaching method. We could not detect any energy transfer between AtDCP1 and free YFP as a negative control. Although the actual FRET efficiencies between AtDCP1-CFP and the tails of YFP-labeled XI-1, XI-2, XI-I, and XI-K were different in the two independent experiments, both data sets clearly showed interactions between all myosins and AtDCP1 (Fig. 1C). The specificity of our results was furthermore supported by detecting FRET efficiencies not higher than 0.5%.
between free CFP and YFP fusions of the different myosin tails (Supplemental Fig. S1B). Negative FRET efficiencies of −1.8% and −1.6% between free CFP and YFP fusions in the cases of XI-2 and XI-I tails, respectively, are likely due to protein degradation that we observed over time.

The Interaction between Myosins and DCP1 Is Conserved in Mammals and Yeast

The finding that DCP1 interacts with myosins in Arabidopsis prompted us to test whether this interaction is conserved in other species. Toward this end, we...
tested the interaction of the yeast Myo2p and the mammalian MyoVa with the respective DCP1 proteins. We found direct interactions between yeast Myo2p and DCP1p and between mouse MyoVa and both human DCP1 homologs in yeast two-hybrid assays and in coprecipitation experiments using bacterially expressed proteins. In addition, we also found interspecies interactions between yeast Myo2p and mouse MyoVa with human, yeast, and Arabidopsis DCP1 (Table I; Fig. 2). Our data indicate that the physical interactions between myosins and DCP1 are evolutionarily conserved.

AtDCP1 Interacts with Class XI Myosin Tails at P-Bodies

To localize the interaction between AtDCP1 and the different class XI myosin tails in planta, we performed bimolecular fluorescence complementation (BiFC) assays in *Nicotiana benthamiana* leaf epidermal cells. BiFC interactions were found at mobile dots that colocalized almost completely with AtDCP2, another well-established marker for P-bodies (Xu et al., 2006). This demonstrates that the interactions between AtDCP1 and the tails of XI-1, XI-2, XI-I, and XI-K occur at P-bodies (Fig. 3; Tables II and III). RabD1 was used as a positive control to show BiFC interactions with XI-1 (Supplemental Fig. S2) and as a negative control for AtDCP1, revealing the specificity of AtDCP1’s interactions with the myosin tails. The N-terminal part of YFP was included as a negative control for the myosin interactions (Supplemental Fig. S3; Tables II and III).

P-Bodies Show Distinct Motility Patterns

The direct interaction between class XI myosin tails and AtDCP1 at P-bodies strongly suggested a function of myosins in P-body movement. Therefore, we characterized the movement of P-bodies in the elongated Arabidopsis leaf midvein epidermal cells using fluorescent tag fusions of AtDCP1 in transient expression assays (Supplemental Movie S1). The tracking of each P-body yielded a trajectory, a sequence of single steps recorded by speed and angle of movement relative to...
We focused our analysis on the motility pattern by considering only steps in which movement occurred (Fig. 4A). Steps were classified into fast (respectively slow) and directed (respectively anisotropic) moves. We found a strong association between fast and directed moves and between slow and anisotropic moves (odds ratio of 10, \( P < 10^{-10}\) in a Fisher test). The median values of all steps were used as the thresholds for the classification of the whole trajectories of P-bodies and thereby to define P-body motility classes (Fig. 4B; see “Materials and Methods”). This strategy led to the definition of four classes: immobile, fast and directed, slow and anisotropic, and “other” movers (Fig. 4C). Interestingly, the path of fast and directed P-bodies often showed spontaneous turns of the P-bodies into the opposite direction. About 9% of all steps from this P-body class were backtracking moves, as defined by a change of directionality of more than 150° (Supplemental Fig. S4B).

The recent finding that P-body movement in Arabidopsis requires an intact actin cytoskeleton (Hamada et al., 2012) raised the question of whether all types of movement are actin dependent. The role of microtubules in P-body movement was studied by treatment with the microtubule depolymerization agent oryzalin in Columbia-0 (Col-0) leaves cotransfected with AtDCP1-mCherry and MICROTUBULE-ASSOCIATED PROTEIN4 (MAP4)-eGFP (Fig. 5, A–C; Supplemental Fig. S5, A and B; Supplemental Movies S2–S5). In contrast to oryzalin treatments, the application of the actin depolymerization drug latrunculin B inhibited the movement of P-bodies efficiently in cells expressing the actin marker Lifeact-eGFP and AtDCP1-mCherry (Fig. 5, A, D, and E; Supplemental Fig. S5, C and D; Supplemental Movies S6–S9). A \( \chi^2 \) test (significance level 1% after Bonferroni multiple testing correction) revealed no significant differences in the motility classes after oryzalin treatment and significant changes after latrunculin B treatment. Consistent with previous (Hamada et al., 2012) and our own drug inhibitor experiments, we additionally observed close associations between transiently expressed CFP fusions of AtDCP1 and the actin cytoskeleton in living plants expressing the F-actin marker Lifeact-eGFP (Era et al., 2009; Fig. 6A).

**P-Body Movement Is Inhibited by Coexpression of Myosin Tails**

Myosin tail fragments are known to exert a dominant negative effect on the motility of their putative
cargo in plant cells (Prokhnevsky et al., 2008; Sparkes et al., 2008; Avisar et al., 2009; Sattarzadeh et al., 2013). To investigate whether they also inhibit the mobility of AtDCP1-labeled P-bodies, we compared the P-body motility class frequency in AtDCP1-expressing cells with P-body movement in cells coexpressing AtDCP1 and one of the myosin tails under consideration (Fig. 6B; Supplemental Movies S10–S13). Overexpression of the tails from XI-1, XI-2, XI-I, and XI-K resulted in a strong reduction of fast and directional moving P-bodies (χ² test, significance level 1% after Bonferroni multiple testing correction). In the case of XI-1, XI-2, and XI-K, this motility reduction was accompanied by a significant increase of nonmoving P-bodies (χ² test, significance level 1% after Bonferroni multiple testing correction). The coexpression of the tail from XI-K led to a significant increase of nonmoving P-bodies (χ² test, significance level 1% after Bonferroni multiple testing correction).

### Analysis of P-Body Movement in Myosin Mutants

The reduced P-body mobility due to coexpressed myosin XI truncations pointed to a possible competition between exogenous and endogenous myosins for cargo binding, which would result in an uncoupling of P-bodies from actin filaments. To test this hypothesis, we studied P-body movements in two mutant alleles of each investigated myosin: xi-1-1 and xi-1-2 (for the myosin XI-1 gene), xi-2-1 and xi-2-4 (for the myosin XI-2 gene), xi-i-1 and xi-i-2 (for the myosin XI-I gene), and xi-k-2 and xi-k-8 (for the myosin XI-K gene; Supplemental Table S1). YFP fusions of AtDCP1 were transiently expressed in leaves of homozygous mutants (Fig. 6C; Supplemental Fig. S6). In comparison with the wild type, both xi-k alleles but none of the other myosin mutants studied showed a significant decrease of the fast and directional moving P-bodies (χ² test, significance level 1% after Bonferroni multiple testing correction). Additionally, the class of slow and anisotropic moving P-bodies was significantly increased (Supplemental Fig. S7, A and B). The mutant analysis suggests that the fast and directed P-body transport is mediated predominantly by myosin XI-K. Given that all four tested myosin tail domains bind to AtDCP1, it is likely that the dominant negative inhibition of P-body movement by the other three myosins is caused by a competition for binding sites. It is possible that they act partially redundantly with XI-K and that their contribution was not seen in the single mutants.

### AtDCP1 Colocalizes with the Full-Length Myosin XI-K

To independently confirm that myosin XI-K is the primary myosin for the fast and directed P-body movement, we analyzed transiently transformed AtDCP1-CFP in leaf epidermal cells of the myosin xi-I xi-2 xi-k triple mutant carrying the genomic full-length myosin XI-K fused to YFP driven by its native promoter, which was shown to rescue the morphological phenotype of the triple mutant (Peremyslov et al., 2012). As reported before, full-length myosin XI-K broadly labeled the actin cytoskeleton. Occasionally, we observed full-length myosin XI-K-labeled dot-like structures. The analysis of AtDCP1-labeled P-bodies in the xi-1 xi-2 xi-k triple mutant carrying the genomic full-length myosin XI-K-YFP line revealed a rescue of their motility (Fig. 6C; Supplemental Fig. S7, A and B). This indicates that myosin XI-K is essential for fast and directional P-body transport.

### Table II. Statistical analysis of BiFC studies, negative controls (related to Fig. 3 and Supplemental Figs. S2 and S3)

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**Table III. Statistical analysis of BiFC studies, positive controls and experimental samples (related to Fig. 3 and Supplemental Figs. S2 and S3)**

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ND, Not determined.
directed P-body movement and sufficient to overcome at least the requirement of XI-1 and XI-2 in Arabidopsis (Supplemental Movie S14). In these experiments, AtDCP1-CFP dots exhibited a close association with myosin XI-K-YFP-labeled F-actin-like structures (Fig. 7A). A meaningful colocalization analysis of AtDCP1-CFP and XI-K-YFP was only possible at thin actin strands with clearly visible XI-K-YFP dots. There, we reliably found myosin colabeling with AtDCP1-CFP (Fig. 7B). About 20% to 30% of the AtDCP1-CFP-labeled P-bodies were associated with distinct actin strands and showed no dots for XI-K-YFP. As the XI-K-YFP signal was generally very weak, we cannot decide whether XI-K-YFP dots are present but below the detection limit or AtDCP1-CFP does not exhibit colocalization in these cases.

Figure 4. P-body movement in Arabidopsis. A, Scatterplot of the speed (x axis) and angle (y axis) values of all single steps. The density of dots is indicated by color, with blue dots representing low densities and yellow dots representing high densities. The vertical green line indicates the median speed value of all single steps (1.3 μm s⁻¹). The horizontal red line indicates the median angle of all single steps (34°). B, Scatterplot of the median speed (x axis) versus the median angle (y axis) of P-body trajectories. The vertical green line indicates the median speed of all single steps (1.3 μm s⁻¹) used to classify P-bodies as fast or slow movers. The horizontal red line indicates the median angle of all single steps (34°) used to classify P-bodies as directed or anisotropic movers. The three movement classes fast and directed, slow and anisotropic, and others are indicated. C, Distribution of P-body motility classes in Col-0.
In order to substantiate the colocalizations found in these experiments, we aimed to demonstrate not only colocalization but also comovement. Toward this end, we performed transient expression assays. XI-K-YFP showed a similar intracellular localization pattern to that in the transgenic rescue line expressing the full-size genomic XI-K-YFP. We frequently found

![Figure 5](image-url)

Figure 5. P-body movement is actin dependent. A, Frequency changes of P-body motility classes relative to Col-0 after drug treatment with latrunculin B (left) and oryzalin (right) in wild-type leaf midvein cells expressing the P-body marker AtDCP1-YFP. The star denotes a condition resulting in a significant change in P-body motility class frequency relative to Col-0 ($\chi^2$ test, significance level 1% after Bonferroni multiple testing correction). B, Transient coexpression of AtDCP1-mCherry (magenta) and MAP4-eGFP (green) in wild-type Col-0 before treatment with 40 $\mu$M oryzalin. C, The same cell as in B after treatment (Supplemental Fig. S5, A and B). D, Transient expression of AtDCP1-mCherry (magenta) in Lifeact-eGFP (green) plants before treatment with 20 $\mu$M latrunculin B. E, The same cell as in D after treatment (Supplemental Fig. S5, C and D). Bar = 10 $\mu$m.

![Figure 6](image-url)

Figure 6. The movement of AtDCP1-CFP requires an intact actomyosin system. A, Movement of one AtDCP1-CFP-labeled P-body (arrowheads) along an actin filament in stably transformed Col-0 plants expressing the F-actin marker Lifeact-eGFP. Time-lapse images were taken at 3-s intervals using laser scanning confocal microscopy. Bar = 12 $\mu$m. B, Dominant-negative effect of myosin tail domains on AtDCP1-labeled P-body movement (related to Supplemental Movies S10–S13). Frequency changes of P-body motility classes are shown in cells coexpressing AtDCP1-CFP in combination with a fluorescence-tagged myosin tail relative to AtDCP1-CFP-expressing cells. C, P-body motility class frequency changes in myosin single mutants and the xi-1 xi-2 xi-k triple mutant carrying YFP-tagged full-size myosin XI-K (rescue line) relative to Col-0 (related to Supplemental Fig. S7). Stars denote experimental setups resulting in significant changes in P-body motility class frequencies relative to Col-0 ($\chi^2$ test, significance level 1% after Bonferroni multiple testing correction).
AtDCP1-labeled P-bodies moving in regions of XI-K-YFP-labeled actin (Fig. 7C, arrows). In cases where we found AtDCP1-labeled dots at distinct thin actin strands, we could observe a clear colocalization and comovement of AtDCP1 and XI-K-YFP, indicating that XI-K-YFP colocalizes with AtDCP1-labeled P-bodies (Fig. 7C; Supplemental Movie S15).

DISCUSSION

Our findings that myosin tail domains physically interact with the respective DCP1 in mammals, yeast, as well as plants, and the further observation that class XI myosins are required for P-body transport in Arabidopsis, shed new light on the molecular mechanism underlying P-body transport. In contrast to organelles, in which membrane-associated adapter proteins provide the link to motor molecules, P-bodies are ill-defined RNA/protein agglomerations that appear to have a set of core proteins in common (Eulalio et al., 2007; Beckham and Parker, 2008). Our data suggest that one of these core components, DCP1, acts as a direct anchor for motor molecules.

What Are the Cargos of Plant Myosins?

The rapid trafficking of various intracellular compartments depends on the function of the sporophytically expressed class XI myosins (Avissar et al., 2008b; Ueda et al., 2010; Peremyslov et al., 2012). In addition, colocalization experiments revealed associations between the respective compartments and class XI myosins. By using marker proteins for Golgi stacks,
peroxisomes, mitochondria, as well as other endomembrane compartments, a partial colocalization of XI-1 and XI-2 truncations with peroxisomes could be observed (Hashimoto et al., 2005; Reisen and Hanson, 2007). A partial overlap with Golgi stacks was reported for subdomains of XI-1 (Reisen and Hanson, 2007) and also for the full-length myosin XI-K (Peremyslov et al., 2012). A direct binding of myosins to any of these compartments through adapter proteins was not shown so far. RabD1 and RabC2A have been identified as XI-2 interactors and, therefore, are good candidates for mediating myosin interactions with cellular compartments. RabC2A localizes to peroxisomes and RabD1 to punctate structures associated with Golgi stacks and the trans-Golgi network (Hashimoto et al., 2005; Pinheiro et al., 2009), suggesting that XI-2 mediates the movement of these compartments through binding to the two Rab proteins. Recently, a new class of plant-specific transport vesicles has been identified and was shown to be directly associated with myosin XI-K via their DUF593 domain-containing receptor MyoB1 (Peremyslov et al., 2013). The authors provide a working model that explains the movement of organelles and other compartments by their transient association to actively transported MyoB vesicles or by following the hydrodynamic flow in the cell. Our data indicate that this model cannot be adopted to explain P-body movement. This is suggested by several findings.

First, like the MyoB proteins (Peremyslov et al., 2013), AtDCP1 acts as an anchor protein mediating the direct interaction between membraneless P-bodies and the main sporophytically expressed class XI myosins. The physical interaction between the tails of the investigated myosin class XI members and the P-body core component AtDCP1 was confirmed by three independent approaches and shown to occur at P-bodies using BiFC assays. In addition, we demonstrate that the full-size myosin XI-K can localize to P-bodies. However, it was not possible to functionally test the role of AtDCP1 in P-body movement, as dcp1 mutants are lethal (Xu et al., 2006). Second, we demonstrate that the regular distribution of P-bodies in the cytoplasm of plant cells is achieved by an active process, namely the movement by different myosin class XI members. The movement of P-bodies seems to be specifically regulated, as we identified two different mobility classes (fast and directional; slow and anisotropic) and a stationary fraction. As the fast and directed P-body transport is significantly reduced solely in myosin xi-k mutants, myosin XI-K seems to be essential for P-body movement. Third, 9% of the fast and directionally moving P-bodies spontaneously change their movement to the opposite direction. In particular, the single steps occur preferentially either in a straight forward or straight backward direction (Supplemental Fig. S4B). This is not consistent with a passive movement. Together, these three lines of argument confirm our conclusion of an active myosin XI-K-powered transport of fast and directed moving P-bodies in Arabidopsis. As myosin XI-K was shown to bind predominantly to MyoB receptors (Peremyslov et al., 2013), it is likely that only a minor fraction of the myosin XI-K proteins bind to P-bodies in vivo, possibly in a competitive manner. The idea that XI-K binds to different cargos in a competitive manner is further supported by recent work showing that plant myosin XI-I not only binds vesicle-anchored MyoB receptors but also the outer nuclear membrane receptors WPP DOMAIN INTERACTING TAIL-ANCHORED PROTEIN1 (WIT1) and WIT2 (Tamura et al., 2013). This behavior is like that in yeast, where Myo2p binds competitively to multiple cargoes (Eves et al., 2012).

DCP1 as a P-Body Anchor for Myosins

At first glance, the molecular mechanism underlying P-body movement differs between animals and plants, in that plants use the actin cytoskeleton (Hamada et al., 2012) whereas animals utilize microtubules (Aizer et al., 2008). In animals and yeast, however, the actomyosin system has been implicated in the assembly and disassembly of P-bodies (Chang et al., 2008; Lindsay and McCaffrey, 2011). Human myosin Va colocalizes with P-body markers and is required for P-body integrity. In addition, myosin Va is suggested to couple P-bodies in collaboration with kinesins to microtubules, as also reported for other cargo (Huang et al., 1999; Ali et al., 2008; Hodges et al., 2009; Lindsay and McCaffrey, 2011). In yeast, Myo2p associates with P-bodies and has also been implicated in P-body integrity (Chang et al., 2008). It is conceivable that the role of myosins in the assembly/disassembly of P-bodies is due to a function in the transport of mRNA/P-body components to and possibly away from P-bodies. Together with our observation that myosins are essential for P-body motility in plants, it is tempting to speculate that the role of myosins in aspects of P-body function is evolutionarily conserved. This view is supported by our finding of an evolutionarily conserved physical interaction between myosin tails and one evolutionarily highly conserved core component of P-bodies. Given that previous studies have identified only nonconserved interactions for plant myosins (Li and Nebenführ, 2008), it is remarkable that myosins and DCP1 from yeast, mammals, and plants interact not only interspecifically but also intraspecifically. In mammals and yeast, this interaction might serve as an identifier tag to facilitate the short-range transport of P-body components to P-bodies, whereas in plants, the same interaction was adapted to mediate the transport of P-bodies over long distances along actin.

MATERIALS AND METHODS

Plant Material

The Arabidopsis (Arabidopsis thaliana) myosin mutants used in this study are listed in Supplemental Table S1 (Ojangu et al., 2007; Peremyslov et al., 2013).
2008; Ueda et al., 2010). Positions of all transfer DNA (T-DNA) insertions were confirmed by sequencing the flanking genomic regions (Supplemental Fig. S6A). Total RNA of homozygous mutants was isolated (Qiagen RNAeasy Kit) and DNase treated (Thermo Scientific), complementary DNA (cDNA) was synthesized (SuperScript III; Invitrogen), and loss of full-length transcript expression was confirmed by quantitative reverse transcription-PCR with three different primer pairs, amplifying cDNA fragments upstream of, downstream of, and spanning the T-DNA insertion sites (Supplemental Fig. S6).

Plasmids
DNA sequences corresponding to the C-terminal tail regions of myosin XI-1 (AT1G17580), XI-2 (AT5G43900), XI-1 (AT1G33200), and XI-K, as well as the genomic sequence of the full-size XI-K (AT5G20490), were described previously (Reisen and Hanson, 2007; Peremyslov et al., 2012). Coding sequences of AIDCPI (AT1G8370), AIDCPI (AT1G3570), and XI-2 tail including the collodion region were amplified from Arabidopsis Col-0 cDNA; DCPIp (Q12517) and Myo2p (P19524) from yeast strain AH109; and DCPIa (Q18127) and Myo2p (Q16240) from HEK298 cDNA cloned into pDONR201 (Invitrogen) and sequenced. Murine MyoVa tail encoding the last C-terminal 701 amino acids of the melanocyte-specific myosin Va (NP_034994) was amplified with primers containing attB sites on melanoocyte MyoVa long tail in mCherry-C1, which has been described before (Chen et al., 2012), recombined in pDONR201, and sequenced. RabD1 (AT1G17580) was amplified with primers containing attB sites on pUNI clone L50000, recombined in pDONR201, and sequenced. A complete overview of primer pairs used for cloning is given in Supplemental Table S2. The following Gateway destination vectors were used for protein expression in planta: pENSG/pEXSG-YFP (Feys et al., 2005) for N-terminal/C-terminal fusions with YFP, pAMARENA (Marc Jakoby; GenBank accession number XM_001768069) for protein expression in yeast: pENSG/pEXSG-CFP (Feys et al., 2005) for N-terminal/C-terminal fusions with CFP, pAMARENA (Marc Jakoby; GenBank identifier FR591941) for N-terminal fusions with mCherry, pDONR211/pCL113 (J.F. Uhrig, unpublished data) for N-terminal fusion with YFP, pYFP-C and pSYNE/pSYCZE (Walter et al., 2004) for C-terminal fusions with YFP/YFP; for protein expression in yeast: pAS/pACT (Clontech) for N-terminal fusions of the GAL4 binding and activation domain; for protein expression in Escherichia coli: pGEX-2TM-GW (kindly received from Imre Sommssich and Bekir Ullker) for creating fusion proteins with an N-terminal GST tag and a C-terminal His tag, pDEST17 (Invitrogen) for N-terminal fusions with a His-tag, and pETC-40A (EMBL) for N-terminal fusions with an MBP tag.

Yeast Two-Hybrid Assays
The yeast two-hybrid assays, using the yeast strain AH109, were done as described previously (Gietz et al., 1995). Interactions were analyzed by plating double-transformed yeast cells on synthetic dropout interaction medium lacking Leu, Trp, and His supplemented with 5, 10, and 15 mM 3-amino-1,2,3-triazole.

FRET
Dark-grown Arabidopsis cell suspension culture (Landsberg erecta) was transformed as described previously (Berger et al., 2007). After 4 d of incubation, 500-μL cultures were harvested, resuspended in 150 μL of protein extraction buffer (50 mM NaH2PO4/Na2HPO4, pH 7.2, 1 mM EDTA, pH 8, and 0.1% [v/v] Triton X-100), and shaken with glass beads (1.8-2.2 mm; Roth) for 15 min at 1,400 rpm, 8°C in a thermoblock (Eppendorf). After centrifugation (10 min, 15,000 rpm, 4°C), total protein concentrations of the supernatants were determined using the BCA Protein Assay Kit (Thermo Scientific). Fluorescence intensities were measured at the respective wavelengths. Cell lysates were combined with exactly the same ratios between the CFP-tagged donor and the different YFP-tagged acceptor proteins and incubated for 3 h at 4°C on ice. FRET was analyzed in samples containing (1) combined lysates of cells expressing the CFP-tagged donor in combination with free YFP as a negative control, (2) the CFP-tagged donor in combination with a YFP-tagged acceptor, (3) the lysates of untransformed cells as background corrective, and (4) combined lysates of cells expressing free CFP and the YFP-tagged acceptor protein. FRET efficiency was determined by subtracting the emission spectra of background-corrected CFP fusions (405 nm), pre acceptor bleaching (514 nm), from background-corrected emission spectra of CFP fusions post acceptor bleaching. Emission spectra were detected using the Tecan Infinite 200
Analysis of P-Body Movement

P-body movement was analyzed in transiently transformed midvein epidermal cells of rosette leaves of 14- to 18-d-old Arabidopsis plants. Series of 50 consecutive images were obtained by scanning a single plane every 1.6 s by confocal laser scanning microscopy for general P-body motility analyses and every 3 s for drug treatments due to cosoilization of the cytoskeleton. P-body trajectories were determined by manual tracking using the ImageJ Manual Tracker plugin (written by Fabrice Cordelieres, Institut Curie, Orsay, France).

For each experimental setup, we analyzed time-lapse movies of an average of eight cells. Each experimental set is represented by an average of 162 P-bodies that were tracked for a maximum of 50 frames (Supplemental Fig. S4A). Each P-body is characterized by its trajectory (tx,ty), t = 1,…,T. We first identified immobile P-bodies that did not move (change their coordinates) more than two times. For the analysis of the mobile P-bodies, we removed all time points of a trajectory for which the respective P-body did not move in the preceding interval. The pruned trajectories were converted into a sequence of steps consisting of angles and speeds by calculating the angle between two consecutive moves and the mean step distance of the previous move and the current move divided by the time interval between two frames.

The median speed and median angle values from all single steps were plotted (Fig. 4A). The medians of the single-step speeds and angles were determined and used as thresholds to classify the P-body trajectories that were plotted in Figure 4B. P-bodies were classified into fast (respectively slow) movers if the median speed of its trajectory was larger (respectively smaller) than the median speed of 1.3 μm·s⁻¹ (Fig. 4B, green vertical line) of all single-step speeds measured. Analogously, P-bodies were classified as directed (respectively anisotropic) if the median angle of its trajectory was smaller (respectively larger) than the median angle of 34° (Fig. 4B, red horizontal line) of all single-step angles measured.

Sequence data from this article can be found in the GenBank/EMBL data libraries under accession numbers XI-I (AT1G17580), XI-2 (AT1G34390), XI-I (AT4G33200), XI-K (AT5G20490), AtDCP1 (AT1G08370), AtDCP2 (AT5G13570), RabD1 (AT3G11730), DCP1p (Q12517), Myo2p (P19524), DCP1a (Q9NPI6), DCP1p (Q8IZD4), and MyoVa (NP_034994).

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure S1. Additional control experiments (related to Figs. 1 and 2).

Supplemental Figure S2. Confocal images of N. benthamiana epidermal leaf cells expressing BIFC-positive controls (related to Fig. 3; Tables II and III).

Supplemental Figure S3. Confocal images of N. benthamiana epidermal leaf cells expressing BIFC-negative controls (related to Fig. 3; Tables II and III).

Supplemental Figure S4. Scatterplot of P-body movement.

Supplemental Figure S5. Tracks of AtDCP1-labeled P-bodies under different conditions in transiently transformed Arabidopsis cells at three different time points (related to Fig. 5).

Supplemental Figure S6. Arabidopsis T-DNA insertion lines (related to Fig. 6C).

Supplemental Figure S7. Median speed and median angle of P-body trajectories.

Supplemental Table S1. Arabidopsis myosin XI mutants used in this study.

Supplemental Table S2. Sequences of primer pairs used for cloning.

Supplemental Movie S1. P-body movement in an Arabidopsis leaf epidermis cell transiently expressing YFP-tagged AtDCP1.


Supplemental Movie S3. Movement of AtDCP1-labeled P-bodies in an Arabidopsis leaf epidermis cell before oryzalin treatment (same cell presented in Supplemental Movie S2 without manual tracking).


Supplemental Movie S5. Movement of AtDCP1-labeled P-bodies in an Arabidopsis leaf epidermis cell after oryzalin treatment (same cell presented in Supplemental Movie S4 without manual tracking).


Supplemental Movie S10. Movement of AtDCP1-labeled P-bodies in an Arabidopsis leaf epidermis cell coexpressing the tail of XI-I.


Supplemental Movie S12. Movement of AtDCP1-labeled P-bodies in an Arabidopsis leaf epidermis cell coexpressing the tail of XI-I.

Supplemental Movie S13. Movement of AtDCP1-labeled P-bodies in an Arabidopsis leaf epidermis cell coexpressing the tail of XI-K.

Supplemental Movie S14. Movement of AtDCP1-labeled P-bodies in an Arabidopsis leaf epidermis cell in the myosin xi-1 xi-2 xi-3 triple mutant rescued with the genomic full-length myosin XI-K fused to YFP (Peremyslov et al., 2012).

Supplemental Movie S15. Comovement of AtDCP1-mCherry and genomic full-length XI-K-YFP in a cotransfected Arabidopsis leaf epidermis cell.

ACKNOWLEDGMENTS

We thank Valera V. Peremyslov and Valerian V. Dolja for providing full-length XI-K-YFP and stably transformed xi-k xi-1 xi-2 XI-K-YFP plants, Amirali Sattarzadeh and Maureen Hanson for the generous gift of pENTR clones containing the myosin tails, Jennifer Lippincott-Schwartz for providing the tail of mammalian myosin Va, Joachim Uhrig for the pCL112/pCL113 vectors, Philipp Thomas for providing Liveact-eGFP plants and the corresponding plasmid, and Arijit Das for discussions on P-body movement analysis.

Received November 24, 2013; accepted February 12, 2014; published February 13, 2014.

LITERATURE CITED


