The Caenorhabditis elegans Gene mfap-1 Encodes a Nuclear Protein That Affects Alternative Splicing

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The *Caenorhabditis elegans* Gene *mfap-1* Encodes a Nuclear Protein That Affects Alternative Splicing

Long Ma¹*, Xiaoyang Gao¹, Jintao Luo¹, Liange Huang¹, Yanling Teng¹, H. Robert Horvitz²*

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Abstract

RNA splicing is a major regulatory mechanism for controlling eukaryotic gene expression. By generating various splice isoforms from a single pre-mRNA, alternative splicing plays a key role in promoting the evolving complexity of metazoans. Numerous splicing factors have been identified. However, the *in vivo* functions of many splicing factors remain to be understood. *In vivo* studies are essential for understanding the molecular mechanisms of RNA splicing and the biology of numerous RNA splicing-related diseases. We previously isolated a *Caenorhabditis elegans* mutant defective in an essential gene from a genetic screen for suppressors of the rubberband *unc* phenotype of *9*(*e1500*) animals. This mutant contains missense mutations in two adjacent codons of the *C. elegans* microfibrillar-associated protein 1 gene *mfap-1*. *mfap-1*(n564 n5214) suppresses the *Unc* phenotypes of different rubberband *Unc* mutants in a pattern similar to that of mutations in the splicing factor genes uaf-1 (the *C. elegans* U2AF large subunit gene) and sfa-1 (the *C. elegans* SF1/BBP gene). We used the endogenous gene *tos-1* as a reporter for splicing and detected increased intron 1 retention and exon 3 skipping of *tos-1* transcripts in *mfap-1*(n564 n5214) animals. Using a yeast two-hybrid screen, we isolated splicing factors as potential MFAP-1 interactors. Our studies indicate that *C. elegans* *mfap-1* encodes a splicing factor that can affect alternative splicing.

Introduction

RNA splicing removes non-coding introns and joins adjacent coding exons from pre-mRNAs to generate functional coding mRNAs. Alternative splicing can generate numerous splice isoforms from the same pre-mRNA [1]. The complex proteome encoded by mRNA splice isoforms is believed to be a major driving force for the evolving complexity of metazoans [1,2]. Numerous proteins and non-coding RNAs regulate RNA splicing [3]. The U1 snRNP complex and the SF1/U2AF65/U2AF35 protein complex recognize the 5’ and 3’ splice sites of an intron, respectively [4–11], and the U2 and U4/U5/U6 snRNP complexes assemble in a step-wise manner and undergo compositional and conformational rearrangements to drive the two steps of the trans-esterification reaction in RNA splicing [7,12]. Mutations in trans-splicing factors or cis-regulatory splicing elements cause numerous diseases [13,14].

Over 200 protein factors have been shown to regulate splicing or associate with the splicing machinery or other splicing factors [3]. Splicing factors have been identified mostly using biochemical approaches, and the *in vivo* functions of many splicing factors remain largely unknown. *In vivo* analysis of these factors remains a challenge, since many are essential for viability and the analyses of their *in vivo* functions can be limited by the lethality caused by mutations in these factors.

Recent studies indicate that conclusions concerning splicing factors derived from *in vitro* analyses should be complemented by *in vivo* analyses. For example, *in vivo* studies suggest that the splicing factor SF1/BBP, once thought to be ubiquitously required for splicing, might be required for the splicing of only a subset of genes [15–17]. Some *Saccharomyces cerevisiae* core splicing factors, once thought to be essential for the splicing of all introns, were found to affect splicing of only a subgroup of introns when the effects of loss-of-function mutations in these factors were examined [18]. Also, the functions of some splicing factors extend beyond regulating RNA splicing. For example, the U2AF large subunit is required for the efficient export of intronless mRNAs in *Drosophila* in addition to its essential role in regulating 3’ splice site recognition [19]. Thus, *in vivo* functional analyses are essential for an accurate understanding of the biological functions of splicing factors.

In *Caenorhabditis elegans*, the genes *unc-93*, *sup-9* and *sup-10* encode components of a presumptive two-pore domain K+ channel complex that affects muscle activity [20–23]. Animals carrying rare gain-of-function (gf) mutations in any of these three genes are sluggish, defective in egg laying and exhibit a rubberband phenotype: when touched on the head, the animal contracts and relaxes along its entire body without moving backwards. Complete loss-of-function (lf) mutations of *unc-93*, *sup-9* or *sup-10* do not cause obvious abnormalities [21,22]. The SUP-
n4564 n5214 contains two missense mutations in the gene mfa1-1, which encodes a highly conserved nuclear protein

We cloned the gene affected by n4564 n5214 by genetic mapping and transgene rescue experiments (Figure 1A, 1B; see Materials and Methods). The n4564 n5214 strain contains two missense mutations in the gene F43G9.10, changing the adjacent conserved amino acids Asp 426 and Thr 427 to Val (n4564) and Ala (n5214) in the predicted protein, respectively (Figure 1C). F43G9.10 encodes the C. elegans ortholog of a highly conserved mammalian protein that has been called “microfilament-associated protein 1” (41% identity between the C. elegans and human orthologs) (Figure 1D). We named n4564 n5214 MFAP-1.

Table 1. Suppression of the rubberband Unc phenotype by mfa1-1 mutations.

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<th>Genotype</th>
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<td>wild-type</td>
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<td>wild-type (25°C)</td>
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<td>unc-93(n200) (29)</td>
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<tr>
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Results

n4564 n5214 suppresses the rubberband Unc phenotype of unc-93(e1500) animals

Previously we performed a genetic screen for mutations that caused sterility and/or lethality and concurrently suppressed the rubberband Unc phenotype caused by the unc-93(e1500) mutation [29]. Besides uaf1-1(n4564) and sfa-1(n4562), we also isolated the mutation n4564 [29], which we renamed n4564 n5214 in this study (see below). Although the precise mechanisms underlying the suppression of the rubberband Unc phenotypes by the uaf1-1, sfa-1 [29] and n4564 n5214 (see below) mutations remain to be determined, the uaf1-1 and sfa-1 mutations isolated and the splicing of the uaf1-1 target U2AF can provide tools for studying in vivo functions of splicing factor genes [29,30], which we now report include the gene affected by n4564 n5214.

n4564 n5214 mutants exhibited temperature-sensitive lethality; at 15°C, n4564 n5214 homozygous animals grew and behaved similarly to the wild type; at 20°C, mutant animals grew more slowly, had few progeny and were hyperactive (Table 1); at 25°C, the mutant strain was embryonically lethal. n4564 n5214 weakly suppressed the Unc phenotype of unc-93(e1500) animals at 15°C (L. Ma and H. R. Horvitz, unpublished observations) and was a stronger suppressor at 20°C (Table 1). n4564 n5214; unc-93(e1500) animals were as Unc as unc-93(e1500) animals (L. Ma and H. R. Horvitz, unpublished observations), indicating that n4564 n5214 is a recessive suppressor of the Unc phenotype of unc-93(e1500) animals and suggesting that n4564 n5214 causes a reduction or loss of mfa1-1 function. We tested whether n4564 n5214 also suppressed the Unc phenotype caused by the rubberband mutants unc-93(n200), sup-9(n1550) and sup-10(n983), n200 is a weakly semi-dominant unc-93 allele that causes a weak rubberband Unc phenotype [22]. The sup-9(n1550) and sup-10(n983) gain-of-function mutations cause strong and moderate rubberband Unc phenotypes, respectively [20,21,23,31]. n4564 n5214 strongly suppressed sup-10(n983) but did not suppress unc-93(n200) or sup-9(n1550) (Table 1). Thus, n4564 n5214 suppressed the same rubberband Unc mutations as do the uaf1-1(n4560) and sfa-1(n4562) mutations, both of which suppress the rubberband Unc phenotypes of unc-93(e1500) and sup-10(n983) animals but not the rubberband Unc phenotypes of unc-93(n200) or sup-9(n1550) animals [29].

Author Summary

RNA splicing removes intervening intronic sequences from pre-mRNA transcripts and joins adjacent exonic sequences to generate functional messenger RNAs. The in vivo functions of numerous factors that regulate splicing remain to be understood. From a genetic screen for suppressors of the rubberband Unc phenotype caused by the Caenorhabditis elegans unc-93(e1500) mutation, we isolated a mutation that affects a highly conserved essential gene, mfa1-1. MFAP-1 is a nuclear protein that is broadly expressed. MFAP-1 can affect the alternative splicing of tos-1, an endogenous reporter gene for splicing, and is required for the altered splicing at a cryptic 3’ splice site of tos-1. mfa1-1 enhances the effects of the gene uaf1-1 (splicing factor U2AF large subunit) in suppressing the rubberband Unc phenotype of unc-93(e1500) animals. Our studies provide in vivo evidence that MFAP-1 functions as a splicing factor.

9 protein is similar to the mammalian Two-pore Acid Sensitive K+ channels TASK-1 and TASK-3 [20]. sup-10 encodes a novel single-transmembrane domain protein without identified mammalian homologs [20], and unc-93 encodes a multiple transmembrane-domain protein that defines a novel family of proteins conserved from C. elegans to mammals [20,23]. A mammalian UNC-93 homolog, UNC-93b, interacts with Toll-like receptors and regulates innate immune responses [24–28].

We previously screened for new suppressors of the “rubberband” Unc phenotype of unc-93(e1500) animals and isolated mutations affecting the splicing factors U2AF large subunit (UAF1) and SF1/BBP (SFA-1) [29]. Our analysis suggested that mutations in uaf1-1 and sfa-1 result in the suppression of the rubberband Unc phenotype of unc-93(e1500) animals by altering the splicing of the pre-mRNA of an unknown gene [29]. We identified the pre-mRNA of the gene tos-1 as abnormally spliced in uaf1-1 and sfa-1 mutants and determined that tos-1 is a sensitive endogenous reporter for analyzing in vivo functions of splicing factors [30]. In this study, we describe a third isolate, n4564 n5214, from the genetic screen in which we identified the uaf1-1 and sfa-1 mutations [29]. We found that the gene affected by n4564 n5214 encodes a novel splicing factor that affects alternative splicing in C. elegans.
F43G9.10 mfap-1 (microfibrillar-associated protein 1). The chicken ortholog of MFAP-1 was suggested to be an extracellular matrix protein [32]. However, the *Drosophila* ortholog of MFAP-1 (dMFAP1) interacts with the splicing factor DPrp38, is required for normal expression of *t-tubulin* and *sug* (ed25) mRNAs and has been proposed to act as a splicing factor [33]. We found that the expression of a human MFAP1::GFP fusion protein (Hmfp-1) in *C. elegans* body-wall muscles rescued the suppression of unc-93(e1500) by mfap-1(n4564 n5214) (Figure 1B), indicating that the function of MFAP-1 is conserved from nematodes to humans.

We examined the expression pattern of mfap-1 in transgenic animals using a transcriptional fusion reporter construct that drives GFP expression under the control of an approximately 2.5 kb mfap-1 promoter (Figure 2A). We observed strong GFP expression in the intestine, pharynx and vulval muscles (Figure 2A). We also observed GFP expression in the body-wall muscles (Figure 2A), consistent with the finding that body-wall muscle-specific expression of mfap-1 rescued the suppression of the unc-93(e1500) Unc phenotype by mfap-1(n4564 n5214) (Figure 1). Both *C. elegans* MFAP1::GFP and human MFAP1::GFP, when expressed in body-wall muscles, were exclusively localized in nuclei (Figure 2B and unpublished observations), indicating that MFAP-1 is a nuclear protein.

The D426V(n5214) and T427A(n4564) mutations act together to suppress unc-93(e1500)

The temperature-sensitive lethal phenotype of mfap-1(n4564 n5214) at 25°C provided an approach to the identification of genes that interact with mfap-1 by seeking suppressors of the temperature-sensitive lethality. We screened about 50,000 haploid animals at 25°C, since we failed to obtain progeny with this genotype from mfap-1(n4564 n5214); unc-93(e1500) animals. We expressed MFAP-1::GFP and human MFAP1::GFP, when expressed in body-wall muscles, were exclusively localized in nuclei (Figure 2B and unpublished observations), indicating that MFAP-1 is a nuclear protein.

We obtained a 746 bp mfap-1 deletion allele, tm3456A (kindly provided by S. Mitani, personal communication), which removes the entire first intron and most of the second exon of mfap-1 (Figure 1C). tm3456A is predicted to encode a truncated protein with a frameshift after amino acid 53, suggesting that tm3456A is likely a null allele of mfap-1. mfap-1(tm3456A)/+ animals grew and behaved like the wild type, and mfap-1(tm3456A) homozygous animals arrested developmentally at the L1 or L2 larval stages. They became sterile when grown at 20°C, and mfap-1(tm3456A) homozygous animals were apparently healthy at 20°C (L. Ma and H. R. Horvitz, unpublished observations). Furthermore, mfap-1(n5214); uaf-1(n4588) double mutant animals were viable at 15°C but became sterile when grown at 20°C, which is a more severe temperature-sensitive phenotype than that of uaf-1(n4588) single mutants. Therefore, the suppression of the Unc phenotype of unc-93(e1500) animals by mfap-1(n5214) and uaf-1(n4588) mutations might have additive effects on animal survival.

We next examined whether mfap-1(n5214) could enhance the suppressor activities of mfap-1 mutations for the Unc phenotype of unc-93(e1500) animals by generating mfap-1(n2514); uaf-1 double mutant animals carrying the unc-93(e1500) mutation (Table 3). mfap-1(n5214); uaf-1(n5123) double mutants were similar to mfap-1(n5214) or uaf-1(n5123) single mutants and were not substantially suppressed for the Unc phenotype of unc-93(e1500) animals (Table 3). mfap-1(n2514) enhanced the suppressor activity of the unc-93(e1500) mutants. As expected, both mfap-1(n5214); uaf-1(n4588 n5127) and mfap-1(n5214); uaf-1(n4588) strongly suppressed unc-93(e1500), since both unc-93(e1500) and uaf-1(n4588) are strong suppressors for unc-93(e1500) [29]. Although mfap-1(n5214) or uaf-1(n4588 n5127) mutants were apparently healthy at 20°C, mfap-1(n5214); uaf-1(n4588 n5127) mutant animals became partially sterile at 20°C (L. Ma and H. R. Horvitz, unpublished observations). Furthermore, mfap-1(n5214); uaf-1(n4588) double mutant animals were viable at 15°C but became sterile when grown at 20°C, which is a more severe temperature-sensitive phenotype than that of uaf-1(n4588) single mutants. That mfap-1 mutations enhance the temperature-sensitive phenotypes of uaf-1 mutants suggests that mfap-1 and uaf-1 might act in parallel in affecting unc-93 function and animal survival.

We tested if mfap-1(n4564 n5214), like the uaf-1(n4588) mutation [29], would cause the recognition of a cryptic 3' splice site in exon 9 of unc-93(e1500). We did not observe any obviously altered recognition of this cryptic 3' splice site (1.3% for wild type vs. 2% for mfap-1(n4564 n5214) animals) (Figure S1). Therefore, the suppression of the Unc phenotype of unc-93(e1500) by mfap-1(n4564 n5214) might not be caused by altered splicing of the unc-93(e1500) transcript.

mfap-1(n4564 n5214) alters the splicing of tos-1 by increasing intron 1 retention and exon 3 skipping

To analyze whether mfap-1 can affect alternative splicing, we examined the splicing of tos-1 in mfap-1(n4564 n5214) animals. We previously described tos-1 as a sensitive endogenous reporter for alternative splicing in *C. elegans* [30]. As shown in Figure 3A–3C, mfap-1(n4564 n5214) increased tos-1 intron 1 retention and exon 3 skipping, suggesting that the recognition of the 3' splice sites in intron 1 or before exon 3 was reduced in mfap-1(n4564 n5214) animals. We note that the tos-1 splice isoforms we observed in mfap-1(n4564 n5214) and mfap-1(RNAi) animals can also be seen in wild-type animals (Figure 3A), indicating that alterations in mfap-1
Figure 1. Genetic mapping, cloning, and identification of mfap-1. (A) Genomic location of the n4564 n5214 mutation based on genetic mapping using visible markers and SNPs (e.g., SNP T01H8: 7110 on the left and SNP F36A2: 3334 on the right). Cosmids tested in rescue experiments are labeled. Only cosmid F43G9 rescued the three phenotypic characteristics of mfap-(n4564 n5214) individuals: suppression of the Unc phenotype of unc-93(e1500) animals; partial sterility at 20°C; and temperature-sensitive lethality at 25°C. (B) Transgene rescue experiments. Transgenes (nEx) were injected into the gonads of mfap-1(n4564 n5214); unc-93(e1500) animals, and lines stably transmitting the transgenes were established. Transgenic lines were analyzed for the rescue of each of three abnormalities: suppression of the Unc phenotype of unc-93(e1500) animals; partial sterility at 20°C; and temperature-sensitive lethality at 25°C. mut: the n4564 n5214 mutation. (C) Gene structure of mfap-1. Black boxes: coding exons. Open boxes: 5' and 3' UTRs. Positions of start (ATG) and stop codons (TGA) are indicated. The sites of the n4564 n5214 mutation, the n5214 mutation and the tm3456Δ deletion are labeled. (D) Sequence alignment of predicted MFAP-1 proteins from C. elegans, Drosophila, chicken and human. *: amino acids
mutated in mfap-1(n4564 n5214) mutants. Amino acids conserved in at least three orthologs are darkly shaded, while amino acids with similar physical properties or conserved in two orthologs are lightly shaded.

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affect tos-1 alternative splicing events that occur in the wild type. We also examined whether mfap-1(n4564 n5214) could cause recognition of the cryptic 3′ splice site in tos-1 intron 1, which was recognized in uaf-1(n4588) animals [30]. We did not detect obvious recognition of the cryptic 3′ splice sites in mfap-1(n4564 n5214) animals (Figure 3D), suggesting that mfap-1(n4564 n5214) did not alter the specificity of 3′ splice-site recognition. We similarly examined mfap-1(n5214) animals and did not observe obvious effects on the splicing of tos-1 or the recognition of the intron 1 cryptic 3′ splice site (Figure S2B), suggesting that mfap-1(n5214) does not alter or has a very weak effect on tos-1 splicing. This result is consistent with the notion that n5214 is a weaker mfap-1 allele than n4564 n5214.

We next examined the splicing of tos-1 in animals fed dsRNA targeting mfap-1. We observed an apparent increase of tos-1 isoforms 1 and 2 (Figure 4A). Increased expression of isoforms 1 and 2 is caused by increased intron 1 retention and exon 3 skipping in tos-1 splicing, as was seen for mfap-1(n4564 n5214)
animals (Figure 3). The similarity of mdaf-1(n4564 n5214) and mdaf-1(RNAi) in affecting tol-1 splicing further suggests that n4564 n5214 causes a reduction or loss of mdaf-1 function. Reducing mdaf-1 expression by RNAi feeding did not cause the recognition of the cryptic 3′ splice site in intron 1 (Figure 4B). Similarly, that cryptic splice site was not recognized in mdaf-1(n4564 n5214) animals (Figure 3D).

To determine whether uaf-1 mutations and mdaf-1 mutations could interact in affecting RNA splicing, we examined the splicing of tol-1 and the recognition of the cryptic 3′ splice site of tol-1 intron 1 in mdaf-1; uaf-1 mutant animals. For each mdaf-1; uaf-1 mutant, the splicing of tol-1 appeared to be similar to that in the corresponding uaf-1 single mutant or mdaf-1 single mutant (Figure S2A, S2B, top panels). We did not observe additive or synergistic effects of uaf-1 and mdaf-1 mutations on intron 1 retention (Figure S2A, e.g., compare mdaf-1(n4588 n5127) with mdaf-1(n4564 n5214); uaf-1(n4588 n5127) or exon 3 skipping (Figure S2B, e.g., compare mdaf-1(n4564 n5214) with mdaf-1(n4564 n5214); uaf-1(n4588 n5127)). Interestingly, the recognition of the cryptic 3′ splice site was reduced by about 50% in mdaf-1(n4564 n5214); uaf-1(n4588 n5127) and mdaf-1(n5214); uaf-1(n4588 n5127) mutant animals compared to that in uaf-1(n4588 n5127) mutant animals (Figure S2A, S2B, bottom panels and Figure S3C), suggesting that wild-type mdaf-1 function might be required for the recognition of the cryptic 3′ splice site in uaf-1(n4588 n5127) animals.

MFAP-1 interacts physically with known splicing factors in a yeast two-hybrid experiment

To further understand the function of MFAP-1, we sought to identify interacting proteins of MFAP-1 using a yeast two-hybrid screen [see Materials and Methods]. We isolated and retested nine genes encoding proteins that might potentially interact with MFAP-1 (Table S1). Two of the genes, K04G7.11 and D1054.14, encode the C. elegans orthologs of the presumptive splicing factors SYF2 [34] and Ppr38 [35]. Drosophila MFAP-1 (dMFAP1) was found to be in a protein complex with dPpr38 in co-immunoprecipitation experiments and to interact with dPpr38 physically [33]. SYF2 mutations were found to cause synthetic lethality with mutations in splicing factors cfl1Delta2 and prp17/cdc40Delta in S. cerevisiae [34], and mammalian orthologs of SYF2 were identified in various splicingosomal complexes by proteomic approaches [3], suggesting that SYF2 acts as a splicing factor. We also identified MFAP-1 as an interactor in the two-hybrid screen, indicating that MFAP-1 might form homodimers. The other potential interactors are two proteins involved in rRNA processing (C05C8.2 and T22H9.1), a ribosomal protein (RPS-6), a Ras-associated PH-domain containing protein (MIG-10), a Rab11 family-interacting protein 2 (Y39F10B.1) and a protein of unknown function (F43C11.9). Although the interactions between MFAP-1 and the proteins from the yeast two-hybrid screen remain to be verified by other approaches, the observation that two presumptive splicing factors (Ppr38 and SYF2) are among the candidates is consistent with our findings and also those of Andersen and Tapon [33] indicating that MFAP-1 might function as a splicing factor.

We next examined the splicing of tol-1 in animals fed dsRNAs targeting mdaf-1, D1054.14 and K07G7.11 (Figure S4). We found that D1054.14(RNAi) caused an increase of tol-1 splice isoform 2 similar to that seen in mdaf-1(RNAi) animals (Figure S4). No apparent alteration in tol-1 splicing was detected in K07G7.11(RNAi) animals. This result is consistent with previous studies indicating that homologs of D1054.14 can function as splicing factors [33,35] and identified tol-1 as a target of D1054.14 in C. elegans.

**Table 2.** mdaf-1(n4564) and mdaf-1(n5214) are weak mutations that act together to suppress the rubberband Unc phenotype of unc-93(e1500) animals.

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<td>nEx[Pmyo-3 mdaf-1 cDNA (n5214)::GFP] line 3</td>
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<td>20</td>
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<tr>
<td>nEx[Pmyo-3 mdaf-1 cDNA (n4564 n5214)::GFP] line 1</td>
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<td>20</td>
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<tr>
<td>nEx[Pmyo-3 mdaf-1 cDNA (n4564 n5214)::GFP] line 2</td>
<td>14.3±6.4</td>
<td>20</td>
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</table>

All transgenes were expressed in mdaf-1(n4564 n5214); unc-93(e1500) animals. Two lines were obtained and analyzed for transgene Pmyo-3 mdaf-1 cDNA (n4564 n5214)::GFP. doi:10.1371/journal.pgen.1002827.t002

**Table 3.** Mutations in mdaf-1 and uaf-1 interact to affect the locomotion of unc-93(e1500) animals.

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Body-bends per 30 sec ± SD</th>
<th>n</th>
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</thead>
<tbody>
<tr>
<td>wild-type [29]</td>
<td>20.4±3.7</td>
<td>20</td>
</tr>
<tr>
<td>unc-93(e1500) [29]</td>
<td>0.9±1.2</td>
<td>20</td>
</tr>
<tr>
<td>mdaf-1(n5214); unc-93(e1500)</td>
<td>1.8±1.3</td>
<td>20</td>
</tr>
<tr>
<td>mdaf-1(n4564 n5214); unc-93(e1500)</td>
<td>21.8±4.5</td>
<td>20</td>
</tr>
<tr>
<td>uaf-1(n5123) unc-93(e1500) [29]</td>
<td>0.6±0.8</td>
<td>20</td>
</tr>
<tr>
<td>mdaf-1(n4564 n5214); uaf-1(n5123) unc-93(e1500)</td>
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<td>20</td>
</tr>
<tr>
<td>uaf-1(n4588 n5125) unc-93(e1500) [29]</td>
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<td>20</td>
</tr>
<tr>
<td>mdaf-1(n5214); uaf-1(n4588 n5125) unc-93(e1500)</td>
<td>10.2±5.7</td>
<td>20</td>
</tr>
<tr>
<td>mdaf-1(n4564 n5214); uaf-1(n4588 n5125) unc-93(e1500)*</td>
<td>20.5±4.5</td>
<td>20</td>
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<tr>
<td>uaf-1(n4588 n5127) unc-93(e1500) [29]</td>
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<tr>
<td>mdaf-1(n4564 n5214); uaf-1(n4588 n5127) unc-93(e1500)*</td>
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<tr>
<td>mdaf-1(n4564 n5214); uaf-1(n4588) unc-93(e1500)**</td>
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<td>mdaf-1(n4564 n5214)</td>
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<td>20</td>
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<tr>
<td>uaf-1(n5123) [29]</td>
<td>19.1±3.1</td>
<td>20</td>
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<tr>
<td>uaf-1(n4588 n5125) [29]</td>
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<td>20</td>
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<tr>
<td>uaf-1(n4588 n5127) [29]</td>
<td>22.1±4.0</td>
<td>20</td>
</tr>
<tr>
<td>uaf-1(n4588) [29]</td>
<td>23.1±4.1</td>
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</table>

*Sterile at 20°C. **Inviiable. doi:10.1371/journal.pgen.1002827.t003
Discussion

MFAP-1 is essential for animal development

MFAP1 was initially identified as a putative extracellular matrix protein based on a screen of an embryonic chicken cDNA expression library using antibodies against elastic fiber microfibrils-enriched bovine ocular zonule proteins [32]. Our analysis of C. elegans mfap-1 and the study of the Drosophila ortholog dMFAP1 [33] indicate that MFAP-1 orthologs in these two species are nuclear proteins that affect RNA splicing. In addition, the human ortholog of MFAP-1 was found to be associated with spliceosomes by mass spectrometry analysis [36–38]. Since the human ortholog of mfap-1 can rescue the activity of C. elegans mfap-1(n4564 n5214) for suppressing the Unc phenotype of uhc-93(e1500) animals, the function of MFAP-1 is likely conserved from nematodes to humans.

Drosophila dMFAP1 acts with several other splicing factors in G2/M progression during mitosis and affects the ratio of premRNA to mature mRNA of the γ-tubulin gene and the mRNA level of the stg/dcd2 gene [33]. It is not known if dMFAP1 affects alternative splicing [33]. C. elegans mfap-1(n4564 n5214) mutants exhibit a temperature-sensitive phenotype with normal growth at 15°C and embryonic lethality at 25°C; mfap-1(n38456) homozygous animals arrest at L1 to L2 larval stages at 20°C, and mfap-1 RNAi-treated animals arrest at variable larval stages at 20°C (L-Ma and H. R. Horvitz, unpublished observations). These observations indicate that C. elegans mfap-1 is essential for animal development. Whether the developmental defect of mfap-1-deficient animals is caused by mitotic defects remains to be determined.

MFAP-1 is probably required for the recognition of weak 3′ splice sites

We isolated mfap-1(n4564 n5214) from the same genetic screen in which we identified mutations affecting uaf-1 and sfa-1 [29]. mfap-1(n4564 n5214) suppressed the phenotypes of different rubberband Unc mutants in patterns similar to those of uaf-1(n4588) and sfa-1(n4562) mutations. The findings led us to hypothesize that MFAP-1 might function as a splicing factor. Our analysis of tos-1 splicing in mfap-1 mutant animals and in animals treated with mfap-1 RNAi provided molecular evidence that mfap-1 can affect alternative splicing. mfap-1(n4564 n5214) and mfap-1(RNAi) both increased tos-1 intron 1 retention (with a weak 3′ splice site) and tos-1 exon 3 skipping (with a different weak 3′ splice site), and neither affected the splicing of intron 3 (with a strong consensus 3′ splice site TTTCCTAG). These observations suggest that MFAP-1 might be required for the recognition of weak 3′ splice sites and not for the recognition of strong 3′ splice sites. We propose that MFAP-1 can act much like UAF-1 and SFA-1, mutations in which cause reduced recognition of the weak 3′ splice sites in introns 1 and 2 and do not affect the recognition of the consensus 3′ splice site in intron 3 of tos-1 [30]. Similar to sfa-1(n4562), mfap-1(n4564 n5214) or mfap-1(RNAi) did not cause recognition of the cryptic 3′ splice site in tos-1 intron 1, suggesting that MFAP-1 probably is not essential for determining the specificity of 3′ splice sites.

The effects of mfap-1(n4564 n5214) and mfap-1(RNAi) on tos-1 splicing are qualitatively similar but quantitatively different. We also observed differences in the effects on tos-1 splicing by genetic mutations and RNAi treatments in our previous studies of uaf-1 and sfa-1, in which we found that uaf-1(n4588) or sfa-1(n4562) caused more dramatic alterations of tos-1 splicing than did either uaf-1(RNAi) or sfa-1(RNAi). This difference was at least partially caused by an altered function of UAF-1 in uaf-1(n4588) animals [30]. Thus, differing effects on target gene splicing by RNAi-treatment and genetic mutation of a splicing factor gene could be caused by several factors, including the differing level of the splicing factor in RNAi-treated and mutant animals and the effects of mutations on the function of the splicing factor.

MFAP-1 might interact with multiple partners to affect RNA splicing

From a yeast two-hybrid screen, we identified nine candidate MFAP-1-interacting proteins. One, D1054.14, is homologous to the Δ. cerevisiae splicing factor Prp38 [35]. Another, K04G7.11, is orthologous to the Δ. cerevisiae candidate splicing factor SYF2 [34]. Drosophila splicing factors DPrp38 and DSFY1 were found in a protein complex with dMFAP1, and DPrp38 interacts with dMFAP1 in GST-pulldown experiments [33]. We did not identify orthologs of SYF1 or several other splicing factors found in the Drosophila dMFAP1 complex, possibly because the co-immuno- precipitation experiments could have identified Drosophila proteins that did not directly interact with dMFAP1, whereas our yeast two-hybrid screen could identify only proteins that directly interact with MFAP-1. Both studies suggest that MFAP-1 interacts with multiple splicing factors directly or indirectly and hence that MFAP-1 might play multiple roles in affecting RNA splicing.

We found that reducing the expression of D1054.14 by RNAi caused alterations in tos-1 splicing similar to those caused by mfap-1(RNAi) (Figure S4), suggesting that MFAP-1 and D1054.14/PRP38 might interact to regulate the splicing of the same set of genes. We did not identify alterations in tos-1 splicing in animals fed dsRNA targeting K04G7.11, indicating that K04G7.11 might not be required for the splicing of tos-1.

mfap-1 and uaf-1 might interact to affect RNA splicing

We previously concluded that the suppression of the rubberband Unc phenotype of uhc-93(e1500) animals by uaf-1(n4588) and sfa-1(n4562) is probably caused by altered splicing of an unknown gene [29]. The splicing of uhc-93(e1500) appears to be normal in mfap-1(n4564 n5214) animals, indicating that altered splicing of uhc-93(e1500) transcripts similarly is not the cause of the suppression of uhc-93(e1500) Unc phenotype by mfap-1(n4564 n5214).

The uaf-1(n4588) mutation likely causes the recognition of the cryptic 3′ splice site of tos-1 intron 1 by altering rather than decreasing the function of the UAF-1 protein [30]. uaf-1(n4588 n5127) is a weaker mutation than uaf-1(n4588), and the recognition of the cryptic 3′ splice site in uaf-1(n4588 n5127) animals but not in uaf-1(n4588) animals was reduced by the presence of the mfap-1(n4564 n5214) and mfap-1(RNAi) mutations (Figure S3C). These results suggest that the recognition of the cryptic 3′ splice site of tos-1 requires MFAP-1 only if that recognition is already weak as in uaf-1(n4588 n5127) mutants. These results further support our conclusion that MFAP-1 affects alternative splicing.

In short, we propose that MFAP-1 can act as a splicing factor. Future studies should reveal how MFAP-1 interacts with other splicing factors to affect C. elegans development by regulating splicing of its target genes.

Materials and Methods

Strains

C. elegans strains were grown at 20°C as described unless otherwise indicated [39]. N2 (Bristol) was the reference wild-type strain [39]. Other strains used in the study were:

LGL: mfap-1(n4564 n5214, n5214, tm3456Δ) (this study).

MFAP-1 Affects Alternative Splicing

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Figure 3. *mfap-1(n4564 n5214)* affects the splicing of *tos-1*. (A) RT-PCR experiments showing the effect of *mfap-1(n4564 n5214)* on *tos-1* alternative splicing. *tos-1* splice isoforms are illustrated on the right. (B) The molar ratios of all *tos-1* splice isoforms with intron 1 retention (isoforms 1 and 2), presented as a percentage of all isoforms combined (isoforms 1, 2, 3, 4, and 5). Error bars: standard deviations. *p* < 0.05. (C) The molar ratios of all *tos-1* splice isoforms with exon 3 skipping (isoforms 2 and 5), presented as a percentage of all isoforms combined (isoforms 1, 2, 3, 4, and 5). Error bars: standard deviations. *p* < 0.05. (D) RT-PCR experiments showing the effect of the *mfap-1(n4564 n5214)* mutation on the recognition of the cryptic 3' splice site of *tos-1* intron 1. For all analyses, isoform intensities were obtained by analyzing biological duplicates or triplicates using NIH ImageJ software.

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LGII: sup-9(n1550) [20].
LGIII: waf-1(n4588, n5123, n4588 n5125, n4588 n5127) [29], unc-93(e1500, n200) [23], sup-18(n1014) [21].
LGIV: sfa-1(n4562) [29].
LGX: sup-10(n983) [21].
CB4856 (Hawaiian) [40]

We used the genetic translocation hT2[bli-4(e937) let-7(q782) qIs48] LG I; LG III [41], which carries an integrated pharyngeal GFP element [42], to balance the mfap-1(tm3456) mutation.

Cloning of mfap-1

We used single-nucleotide polymorphism (SNP) mapping [40] to localize n4564 n5214 to the right of nucleotide 7110 (SNP T01H8: 7110 S = AT) on cosmid T01H8 (T01H8 sequences refer to nucleotides of GenBank accession no. Z80219) and to the left of nucleotide 3334 (SNP F36A2: 3334 S = CT) on cosmid F36A2 (F36A2 sequences refer to nucleotides of GenBank accession no. Z81077) (Figure 1A). We isolated 10 Dpy recombinants after crossing dpy-5(e61) n4564 n5214 hermaphrodites with males of the Hawaiian strain CB4856, and six Unc recombinants after crossing n4564 n5214 unc-75(e950) hermaphrodites with CB4856 males.

Cosmid F43G9 rescued three phenotypic characteristics of the n4564 n5214 strain: suppression of unc-93(e1500), partial sterility and temperature-sensitive lethality at 25°C (Figure 1B). We determined the coding sequences of F43G9.10 and identified two missense mutations (GAT-to-GTT (D426V) and ACA-to-GCA (T427A)) in the fourth exon of F43G9.10 (Figure 1C). The predicted proteins encoded by the F43G9.10 orthologs in C. elegans, Drosophila, chicken and human are highly conserved, and the Asp-Thr dipeptide altered in the mfap-1(n4564 n5214) mutant is completely conserved (Figure 1D). A genomic fragment containing a 2.5 kb promoter region, the entire 1.7 kb coding region and a 1.5 kb 3’ downstream region exhibited rescuing activity similar to that of the F43G9 cosmid (Figure 1B). Transgenes expressing F43G9.10 and or the human ortholog of F43G9.10 (Hsmfap-1) in body-wall muscles each rescued the suppression of unc-93(e1500) by mfap-1(n4564 n5214) (Figure 1B). A transgene carrying the mfap-1(n4564 n5214) mutation (mut) failed to rescue the suppression of unc-93(e1500) by mfap-1(n4564 n5214) (Figure 1B), suggesting that this mutation caused the suppressor activity in mfap-1(n4564 n5214) animals.

Screen for suppressors of mfap-1(n4564 n5214)

Synchronized L4 mfap-1(n4564 n5214) animals (P0) grown at 15°C were mutagenized with ethyl methanesulfonate (EMS) as described [39] and grown to gravid adults at 15°C. The P0 adults were bleached, and their F1 progeny were grown to young adults at 15°C and moved to 25°C. After three days at 25°C, the plates were examined for surviving fertile animals. From about 50,000 haploid genomes (F2) screened, two independent suppressed strains were isolated. As animals with a mfap-1(n4564 n5214) phenotype (partial sterility at 20°C and temperature-sensitive lethality at 25°C) were not identified from about 1800 progeny of mfap-1(n4564 n5214) sup/++ animals, we concluded that the two suppressors were either intragenic or extragenic and very closely linked to mfap-1. DNA sequence determination identified in both suppressors the same

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**Figure 4. Reducing mfap-1 expression by RNA interference alters the splicing of tos-1.** (A) RT-PCR experiments showing the effect of reducing mfap-1 expression by RNAi feeding on tos-1 alternative splicing. tos-1 splice isoforms are illustrated on right. (B) RT-PCR experiments showing the effect of reducing mfap-1 expression by RNAi feeding on the recognition of the cryptic 3’ splice site of tos-1 intron 1.

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nucleotide change (GCA-to-ACA at codon 427), which converted the mutated amino acid alanine in the mfaxp-1(n4564 n5214) mutant to the wild-type threonine (A427T) while retaining the D426V mutation. One of the two isolates was used for subsequent studies, and the single mutation it carried was designated mfaxp-1(n5214).

Yeast two-hybrid screen
We used a yeast two-hybrid screen [43,44] to identify proteins that might interact with MFAP-1. A pACT2.2 C. elegans yeast two-hybrid library (Addgene plasmid 11523, provided by Dr. Guy Caldwell) was used to screen for MFAP-1 interactors. For the bait, a full-length mfaxp-1 cDNA was subcloned into the pGBK T7 plasmid (Clontech) and then transfected into the S. cerevisiae strain P609-4A. pGBK T7-mfaxp-1-positive yeast cells were transfected with 2 μg of DNA from the pACT2.2 yeast two-hybrid library, and cells were grown on a SD-Leu-Trp-His medium with 5 mM 3-AT. Positive clones were picked and grown in separate cultures using the same SD medium. Plasmids were obtained from each clone by the smash-and-grab method [45]. Purified plasmids were transfected into the bacterial strain DH5α and grown on LB-ampicillin plates. Plasmids were purified from the bacterial cultures, and sequences of the inserts were determined. Using yeast two-hybrid assays, we confirmed that these clones did not cause survival of yeast cells transfected with the pGBK T7 empty vector on SD-Leu-Trp-His medium, suggesting that proteins encoded by these clones potentially interact with MFAP-1 but not with the GALA DBD domain expressed by the pGBK T7 vector.

RNA interference
Young adult animals were fed HT115 (DE3) bacteria containing plasmids directing the expression of dsRNAs targeting uaf-1, sfa-1, mfaxp-1, D1054.14 or K047.11 on NGM plates with 1 mM IPTG and 0.1 mg/ml Ampicillin [46]. F1 progeny of these animals, which arrested at various developmental stages, were washed from plates, rinsed with H2O and resuspended in Trizol (Invitrogen) for preparation of total RNA. The DNA construct that expresses dsRNA targeting uaf-1 and the bacterial strain that expresses dsRNA targeting sfa-1 were described previously [29]. We obtained a bacterial strain expressing dsRNA targeting mfaxp-1 from a whole-genome RNAi library [47] and bacterial strains expressing dsRNAs targeting mfaxp-1, D1054.14 or K047.11 from an ORFeome-based RNAi library [40]. The sequences of plasmids from single colonies were determined to confirm the presence of coding sequences for each gene.

Body-bend assay
L4 animals were picked 16–24 hrs before being tested. One day later, young adults were individually picked to plates with OP50 bacteria, and body-bends were counted for 30 sec using a dissecting microscope as described [49].

Molecular biology
Total RNA was purified with Trizol (Invitrogen), and cDNA was generated following the protocol provided with the SuperScript II kit (Invitrogen). PCR was performed with ExpandoCyclers, and DNA products were resolved using agarose gels. NIH ImageJ software was used to quantify tos-1 splice isoforms [30]. The percentages of tos-1 intron 1 retention, exon 3 skipping and the recognition of the intron 1 cryptic 3′ splice were analyzed as described [30]. We performed RT-PCR experiments with animals at different developmental stages and found no indication that tos-1 splicing is regulated developmentally (Figure S5). DNA sequence analysis was performed using an ABI Prism 3100 Genetic Analyzer and an ABI 3730XL DNA Analyzer.

Plasmids
mfaxp-1 cDNAs were amplified by RT-PCR from wild-type, mfaxp-1(n4564 n5214) or mfaxp-1(n5214) animals and subcloned to the pPD93.97 vector in-frame with GFP using BamHI/blunt/Age restriction sites. For constructs expressing the mfaxp-1(n4564) transgene, the n4564 mutation was introduced into the pPD93.97::mfaxp-1DNA construct using a QuickChange Site-Directed Mutagenesis Kit (Stratagene) with primers containing the n4564 mutation. For the plasmid used as bait in the yeast two-hybrid screen, full-length mfaxp-1 cDNA was released from the pGEM-T Easy vector (Promega) with NcoI/blunt/PstI and subcloned in-frame into the pGBK T7 vector (Trp1, Kan') (Clontech) using BamHI/blunt/PstI restriction sites. To construct a P_mfaxp-1::GFP transcriptional fusion transgene, an mfaxp-1 promoter fragment of about 2.5 kb was amplified using PCR and subcloned into the pPD93.79 vector using Pmll/Smal restriction sites.

Transgene experiments
Microinjection of DNA into the syncytial gonad and the generation of animals with germline transmission of transgenes were performed as described [50] with mfaxp-1(n4564 n5214) animals grown at 15°C. DNA injection mixtures generally contained 20 μg/ml 1 kb DNA ladder, 20 μg/ml Arabidopsis genomic DNA and 20 μg/ml of the transgene of interest. When the transgene did not express a GFP fusion protein, 20 μg/ml of pPD95.86-GFP plasmid (which expresses GFP in body-wall muscles) was added to the injection mixture as a visible fluorescence marker.

Supporting Information
Figure S1 mfaxp-1(n4564 n5214) does not obviously affect the altered splicing of unc-93(e1500) exon 9. Real-time RT-PCR was performed as described [29] to quantify the recognition of the cryptic 3′ splice site of unc-93(e1500) exon 9. No apparent difference between unc-93(e1500) and mfaxp-1(n4564 n5214); unc-93(e1500) animals was detected. *: results reported previously by Ma and Horvitz (2009) [29]. (TIF)

Figure S2 mfaxp-1 and uaf-1 mutations do not exhibit additive or synergistic effects on the altered splicing of tos-1. (A) RT-PCR experiments showing the splicing of tos-1 (top panel) or the recognition of the cryptic 3′ splice site of tos-1 intron 1 (bottom panel) in mfaxp-1(n4564 n5214) single or mfaxp-1(n4564 n5214); uaf-1 mutant animals. Genotypes are indicated at the top, and tos-1 splice isoforms on the right. (B) RT-PCR experiments showing the splicing of tos-1 (top panel) or the recognition of the cryptic 3′ splice site of tos-1 intron 1 (bottom panel) in mfaxp-1(n5214) single or mfaxp-1(n5214); uaf-1 double mutant animals. Genotypes are indicated at the top, and tos-1 splice isoforms on the right. (TIF)

Figure S3 Quantification of tos-1 intron 1 retention, exon 3 skipping and the recognition of the intron 1 cryptic 3′ splice site in mfaxp-1; uaf-1 multiple mutant animals. (A) The molar ratios of all tos-1 splice isoforms with intron 1 retention, presented as a percentage of all isoforms combined. Error bars: standard deviations. (B) The molar ratios of all tos-1 splice isoforms with exon 3 skipping, presented as a percentage of all isoforms combined. Error bars: standard deviations. (C) Percentages of tos-1 isoforms spliced at the cryptic 3′ splice site of tos-1 intron 1...
compared to all isoforms spliced at either the endogenous 3’ splice site or the cryptic 3’ splice site. For all analyses, isoform intensities were obtained by analyzing biological duplicates or triplicates using NIH ImageJ software. N.S., no significant difference. (TIF)

Figure S4  Reducing the expression of mafp-1 or D1054.14 by RNA interference altered the splicing of tao-1. RT-PCR experiments showing the effects of reducing the expression of mafp-1, D1054.14 or K04G7.11 by RNAi feeding on tao-1 alternative splicing. mafp-1(RNAi) and D1054.14(RNAi) caused similar alterations in tao-1 splicing, while K04G7.11(RNAi) did not obviously affect the splicing of tao-1. RNAi bacterial strains were obtained from an ORFeome-based RNAi library [48]. (TIF)

Figure S5  The splicing of tao-1 is not regulated developmentally. RT-PCR experiments examining the splicing of tao-1 in animals at different synchronized developmental stages. tao-1 splicing was similar in all developmental stages examined. YA: young adult animals 24 hours after the L4 larval stage. (TIF)

Table S1  Candidate MFAP-1 interactors isolated from a yeast two-hybrid screen. (DOC)

References

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Author Contributions
Conceived and designed the experiments: LM HRH. Performed the experiments: LM XG JL LH YT. Analyzed the data: LM XG HRH. Wrote the paper: LM HRH.

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