Biogenesis and germline functions of piRNAs

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Small interfering RNAs and microRNAs are generated from double-stranded RNA precursors by the Dicer endonucleases, and function with Argonaute-family proteins to target transcript destruction or to silence translation. A distinct class of 24- to 30-nucleotide-long RNAs, produced by a Dicer-independent mechanism, associates with Piwi-class Argonaute proteins. Studies in flies, fish and mice implicate these Piwi-associated RNAs (piRNAs) in germline development, silencing of selfish DNA elements, and in maintaining germline DNA integrity. However, whether piRNAs primarily control chromatin organization, gene transcription, RNA stability or RNA translation is not well understood, neither is piRNA biogenesis. Here, we review recent studies of piRNA production and function, and discuss unanswered questions about this intriguing new class of small RNAs.

Introduction

In 1993, Ambros and colleagues showed that the C. elegans lin-4 gene encodes a small regulatory RNA with complementarity to the lin-14 transcription unit, which it negatively regulates (Lee et al., 1993). These pioneering studies thus identified the first microRNA (miRNA). Small non-coding RNAs have subsequently emerged as powerful experimental tools and as crucial developmental regulators in animals and plants (Baulcombe, 2004; Hannon, 2002; Kloosterman and Plasterk, 2006; Mello and Conte, 2004). 21-nucleotide (nt) small interfering RNAs (siRNAs), now ubiquitously used to experimentally manipulate gene expression, are processed from long, double-stranded RNA (dsRNA) precursors by the Dicer endonucleases. The resulting 21-nt dsRNAs are incorporated into an intermediate RNA-protein complex. Displacement of one of the RNA strands (referred to as the ‘passenger strand’) then produces the mature RNA-induced silencing complex (RISC), which contains a single ‘guide strand’ bound to a member of the Argonaute protein family. When the guide-strand siRNA is perfectly complementary to a target RNA, the Argonaute protein catalyzes sequence-specific endonucleolytic cleavage (for reviews, see Hannon, 2002; Meister and Tuschl, 2004). In vivo, the siRNA pathway destabilizes RNA intermediates generated during the viral life cycle, and thus plays an important role in limiting virus infectivity (Wang et al., 2006). By contrast, miRNAs are derived from stem-loop transcripts encoded by chromosomal genes. Primary stem-loop RNAs (priRNAs) are processed in the nucleus by the ribonuclease Drosha, producing pre-miRNAs that are exported from the nucleus and cleaved in the cytoplasm by a Dicer endonuclease to yield ~22-nt mature miRNAs. These miRNAs associate with Argonaute proteins and induce the homology-dependent downregulation of target gene activity. Imperfect miRNA base-pairing to target transcripts appears to induce translational silencing, whereas perfect base-pairing triggers RNA destruction. Mutations in the miRNA pathway disrupt development and often lead to embryonic lethality (reviewed by Du and Zamore, 2005; Kloosterman and Plasterk, 2006).

Recent studies have revealed a new class of 24- to 30-nt RNAs that are generated by a Dicer-independent mechanism and that interact with a subset of Argonaute proteins related to Piwi (Aravin et al., 2006; Brennecke et al., 2007; Girard et al., 2006; Griva et al., 2006a; Gunawardane et al., 2007; Houwing et al., 2007; Lau et al., 2006; Saito et al., 2006; Vagin et al., 2006; Watanabe et al., 2006), which is required for female and male fertility in Drosophila (Lin and Spradling, 1997). In some systems, these Piwi-interacting RNAs (piRNAs) are primarily derived from transposons and other repeated sequence elements (Brennecke et al., 2007; Gunawardane et al., 2007; Saito et al., 2006), leading to their alternative designation as repeat-associated small interfering RNAs (rasiRNAs) (Aravin et al., 2003). It is now clear that piRNAs can be derived from either repeated or complex DNA sequence elements (Aravin et al., 2007; Brennecke et al., 2007; Houwing et al., 2007), and that rasiRNAs are a subset of piRNAs. We therefore use the more generic term piRNA in the following discussions. Genetic studies in mice, Drosophila and zebrafish indicate that piRNAs are crucial to germline development (Carmell et al., 2007; Chen et al., 2007; Cook et al., 2004; Cox et al., 1998; Cox et al., 2000; Deng and Lin, 2002; Gillespie and Berg, 1995; Houwing et al., 2007; Kuramochi-Miyagawa et al., 2004; Pane et al., 2007; Schupbach and Wieschaus, 1991). However, proteins involved in piRNA production have also been implicated in the control of gene expression in somatic cells (Grimaud et al., 2006; Pal-Bhadra et al., 2002; Pal-Bhadra et al., 2004) and in learning and memory (Ashraf et al., 2006), suggesting that piRNAs might have an impact on a broad range of biological processes.

piRNA production

The 24- to 30-nt length of piRNAs is an indication that they are not derived from a long dsRNA precursor and thus cannot be processed by Dicer. Instead, these small RNAs have been implicated in the control of repetitive DNA sequences (Aravin et al., 2006; Brennecke et al., 2007; Girard et al., 2006; Griva et al., 2006a; Gunawardane et al., 2007; Lau et al., 2006; Saito et al., 2006; Watanabe et al., 2006). Insight into the mechanism of piRNA production has come from studies of their genomic origin and of Argonaute binding in Drosophila (Aravin et al., 2006; Brennecke et al., 2007; Girard et al., 2006; Griva et al., 2006a; Gunawardane et al., 2007; Houwing et al., 2007; Lau et al., 2006; Saito et al., 2006; Vagin et al., 2006). In Drosophila ovaries, the vast majority of piRNAs appear to be derived from a limited number of pericentromeric and telomeric sites that are enriched for retrotransposon sequences (Brennecke et al., 2007). The most abundant piRNAs derive from the antisense strand of retrotransposon sequences, and these RNAs preferentially associate with the Argonaute proteins Piwi and Aubergine (Aub). Sense-strand piRNAs, by contrast, preferentially associate with Argonaute 3 (Ago3) (Brennecke et al., 2007; Gunawardane et al., 2007). Piwi, Aub and Ago3, in complex with piRNAs, can cleave target RNAs between positions 10 and 11 of the guide strand (Gunawardane et al., 2007; Saito et al., 2006). Significantly,
piRNAs from opposite strands tend to have a 10-nt overlap. Furthermore, antisense piRNAs bound to Piwi and Aub show a strong bias toward a U at the 5' end, whereas sense-strand piRNAs tend to have an A residue at position 10 (Brennecke et al., 2007; Gunawardane et al., 2007). Based on these observations, two groups concurrently proposed a ping-pong model of piRNA production, in which Ago3 bound to sense-strand piRNAs catalyzes antisense-strand cleavage at an A:U base-pair that generates the 5' end of antisense piRNAs (Fig. 1) (Brennecke et al., 2007; Gunawardane et al., 2007). The 5' ends of the resulting cleavage products are proposed to associate with Aub or Piwi, with nucleolytic processing of the 3' overhangs generating mature 23- to 30-nt antisense piRNAs (Fig. 1B). The mature antisense piRNA-Ago3 complex is then proposed to bind and cleave sense-strand RNAs, silencing gene expression and generating the 5' end of sense-strand piRNA precursors (Fig. 1D). Processing of the 3' overhang produces mature sense-strand piRNAs, completing the cycle (Fig. 1E). This model is based on studies in Drosophila, but recent findings suggest that a similar mechanism might operate in mouse (Aravin et al., 2007).

Genetic screens in Drosophila have identified several additional factors that are required for piRNA production or function. For example, the armitage and spindle E genes encode putative helicases that are required for piRNA production and for retrotransposon silencing (Aravin et al., 2004; Vagin et al., 2006). These proteins could unwind duplex intermediates formed during piRNA production, target recognition, or cleavage. By contrast, the cutoff gene is required for retrotransposon silencing, but is not needed for piRNA production (Chen et al., 2007). Yeast homologs of Cutoff have been implicated in RNA decay (Kim et al., 2004; Xue et al., 2000). Cutoff might therefore facilitate gene silencing by enhancing the activity of piRNA-Argonaute complexes.

**Compartmentalization of the piRNA pathway**

Recently, the Drosophila Tudor-domain protein Krimper has been implicated in both retrotransposon repression and piRNA production (Lim and Kai, 2007). This protein is a component of nuage, a germline-specific perinuclear structure that has been implicated in RNA processing, and krimper mutations block nuage assembly. Intriguingly, many piRNA-pathway-related proteins accumulate in nuage, which is prominent in nurse cells. The Drosophila oocyte develops in a cyst with 15 nurse cells, which synthesize RNAs and proteins that are transported through ring canals to the oocyte (Spradling, 1993). Nuage was first identified in electron micrographs as an amorphous electron-dense cloud that surrounds the nurse cell nuclei (Allis et al., 1979; Mahowald, 1971). Nuage is enriched for the piRNA-Argonaute complexes. However, piRNA-Argonaute complexes appear to be the catalytically active effectors of the pathway, and these localization studies thus suggest that Piwi mediates nuclear functions for the piRNA pathway, whereas Ago3 and Aub drive cytoplasmic functions (Fig. 2B). We speculate that piRNA biogenesis, which is proposed to require
sense- and antisense-strand Argonaute complexes, takes place in the nuage. In this model, the sense-strand piRNA precursor transcripts are exported to the nuage, where they are cleaved by Aub-antisense piRNA complexes, silencing target gene expression and generating precursors of sense-strand piRNAs. These sense-strand precursors associate with Ago3 and are trimmed to mature length. Ago3-sense-strand complexes then catalyze the cleavage of the antisense transcripts, producing piRNA precursors that associate with Aub and Piwi. Mature Aub complexes then remain in the nuage and function in piRNA production and sense-strand transcript destruction, whereas mature Piwi complexes are imported into the nucleus and mediate heterochromatin assembly and transcriptional silencing, or co-transcriptional RNA destruction. This model is highly speculative, but makes a number of clear predictions and might therefore serve as a useful framework for further studies on piRNA biogenesis.

Genetic studies in Drosophila, mice and zebrafish have provided insight into the biological functions of piRNAs and highlight the significance of these RNAs in germline development. The phenotypes of piRNA-pathway mutations in each of these systems are outlined below.

Stem cell division and axis specification in Drosophila females

Mutations in piRNA-pathway genes were first identified in Drosophila through screens for mutations that disrupt oogenesis and embryonic axis specification (Gilaspie and Berg, 1995; Schupbach and Wieschaus, 1991). Drosophila oogenesis begins with a germline stem cell division that produces a cytosblast, which divides four times with incomplete cytokinesis to produce 16 interconnected cells that form a single oocyte and 15 nurse cells (for a review, see Spradling, 1993). The nurse cells provide most of the RNA and protein components of the oocyte, which remains transcriptionally silent through most of oogenesis. Embryonic axis specification in Drosophila depends on the asymmetric localization of a small number of morphogenetic RNAs in the oocyte. These RNAs are transferred from the nurse cells to the oocyte, where localization is driven by interactions with a polarized microtubule cytoskeleton. Microtubule polarization is controlled by a cascade of germline-to-soma and soma-to-germline signaling events (reviewed by Grunert and St Johnston, 1996). Mutations in piRNA-pathway genes disrupt both stem cell maintenance and oocyte production, and the localization of morphogenetic RNAs in the oocyte during axis specification (Chen et al., 2007; Cook et al., 2004; Cox et al., 1998; Cox et al., 2000; Gillespie and Berg, 1995; Lin and Spradling, 1997; Pane et al., 2007; Schupbach and Wieschaus, 1991).

The piwi gene encodes the founding member of the Piwi class of Argonautes (Cox et al., 1998). Mutations in piwi lead to severe defects in oogenesis, including loss of germline stem cells (Fig. 3A) (Cox et al., 1998; Cox et al., 2000; Lin and Spradling, 1997). Clonal studies indicate that stem cell maintenance and division require piwi expression in the somatic cells that form the stem cell niche. Loss of piwi in the germline, by contrast, reduces stem cell division rates, but does not lead to a loss of stem cells or to a block in oogenesis (Cox et al., 2000). Mutations in other piRNA-pathway genes, including zucchini and squash, also lead to germline stem cell loss (Chen et al., 2007; Pane et al., 2007). It is unclear whether these genes are required in the germline, soma, or both. The molecular functions of Piwi and the piRNA pathway in germline stem cell division and maintenance have not been defined.

Mutations in most piRNA genes in Drosophila, including aubergine, spindle E, armitage, maelstrom, krimper, zucchini and squash, disrupt the localization of dorsal and posterior RNAs (Cook et al., 2004; Gillespie and Berg, 1995; Pane et al., 2007; Schupbach and Wieschaus, 1991). These mutations do not disrupt anterior localization of bicoid mRNA or block oocyte development. Therefore, these genes were initially assumed to control the expression of a specific subset of genes required for anterior-posterior and dorsal-ventral patterning (Cook et al., 2004). Subsequent studies, however, have demonstrated that the dramatic axis-specification defects that are associated with piRNA mutations are a secondary consequence of DNA damage signaling (Chen et al., 2007; Klatenhoft et al., 2007; Pane et al., 2007). These studies suggest that piRNAs have a primary function in maintaining germline DNA integrity.

The link between piRNAs and DNA damage signaling was suggested by studies of Drosophila meiotic DNA-repair genes. Meiotic recombination requires DNA break formation by the Spo11 nuclease (Cao et al., 1990), and Schupbach and colleagues have...
shown that mutations that disrupt meiotic DNA break repair also disrupt anterior-posterior and dorsal-ventral axis specification (Abdu et al., 2002; Ghabrial et al., 1998). Significantly, the Drosophila embryonic patterning defects that are linked to repair mutations are dramatically suppressed by mutations in mei-41 and mnk (also known as loki – FlyBase), which encode the ATR and Chk2 kinases, respectively, which function in DNA damage signaling, and by mutations in mei-W68 (Abdu et al., 2002; Ghabrial et al., 1998), which encodes the fly Spo11 homolog (McKim and Hayashi-Hagihara, 1998). Unrepaired meiotic breaks thus appear to activate the ATR and Chk2 kinases, which in turn trigger the observed axis-specification defects. Recent studies show that the axis-specification defects in armitage, aubergine, cutoff and squash are also suppressed by mei-41 and/or mnk (Chen et al., 2007; Klattenhoff et al., 2007; Pane et al., 2007). Furthermore, armitage, aubergine and spindle E mutations lead to a dramatic accumulation of phosphorylated histone H2Av (γ-H2Av) foci in germline nuclei (Fig. 3B); these foci are generally linked to DNA double-strand breaks (Modesti and Kanaar, 2001). Significantly, mei-W68 (Spo11) does not suppress the patterning defects associated with armitage, or the formation of γ-H2Av foci (Klattenhoff et al., 2007). piRNA mutations, like DNA-repair mutations, thus disrupt axis specification through activation of the ATR/Chk2 pathway. However, unlike DNA-repair-pathway mutations, meiotic breaks are not the source of damage.

All of the Drosophila piRNA-pathway mutations lead to a significant overexpression of retrotransposons (Aravin et al., 2001; Chen et al., 2007; Kalmykova et al., 2005; Pane et al., 2007; Sarot et al., 2004; Vagin et al., 2006), and piwi mutants have been shown to mobilize at least one class of transposon in the male germline (Kalmykova et al., 2005). Retrotransposon mobilization can induce DNA damage (Belgnaoui et al., 2006; Gasior et al., 2006), and high rates of transposon insertion in piRNA mutants could overwhelm the DNA-repair machinery, leading to the breaks that activate ATR and Chk2. However, there is no direct evidence for transposon mobilization in the female germline when piRNA-pathway components are disrupted, and this pathway could have a more direct role in DNA repair, or in establishing chromatin structures that resist damage. Drosophila telomeres are composed of retrotransposon repeats, and piRNA mutations increase the number of these repeats (Savitsky et al., 2006). These findings suggest that piRNA mutations could lead to a loss of telomere protection, leading to the recognition of chromosome ends as DNA breaks. However, it is currently unclear whether the break sites in piRNA-pathway mutations are random, linked to transposon insertions, or restricted to specific chromatin domains, and the precise functions of these RNAs in maintaining germline genome integrity remain to be determined.

The Oskar protein is essential for pole plasm assembly and for embryonic patterning, and piRNA-pathway mutations disrupt osk mRNA and protein localization (Cook et al., 2004). The translation of osk mRNA is tightly linked to its posterior localization, which begins during stage 9 of oogenesis (Kim-Ha et al., 1995; Markussen et al., 1995; Rongo et al., 1995). Mutations in a number of piRNA-pathway mutations lead to Oskar protein expression during earlier stages of oogenesis, and the mnk (Chk2) mutation does not suppress premature osk mRNA translation (Cook et al., 2004; Pane et al., 2007). Therefore, premature Osk protein...

**Fig. 3. The piRNA pathway is required for germline development.** (A) piwi is required for the self-renewing division of germline stem cells (Chen et al., 2007; Pane et al., 2007; Sarot et al., 2004; Vagin et al., 2006), and miwi2 mutants have been shown to mobilize at least one class of transposon in the male germline (Kalmykova et al., 2005). Retrotransposon mobilization can induce DNA damage (Belgnaoui et al., 2006; Gasior et al., 2006), and high rates of transposon insertion in piRNA mutants could overwhelm the DNA-repair machinery, leading to the breaks that activate ATR and Chk2. However, there is no direct evidence for transposon mobilization in the female germline when piRNA-pathway components are disrupted, and this pathway could have a more direct role in DNA repair, or in establishing chromatin structures that resist damage. Drosophila telomeres are composed of retrotransposon repeats, and piRNA mutations increase the number of these repeats (Savitsky et al., 2006). These findings suggest that piRNA mutations could lead to a loss of telomere protection, leading to the recognition of chromosome ends as DNA breaks. However, it is currently unclear whether the break sites in piRNA-pathway mutations are random, linked to transposon insertions, or restricted to specific chromatin domains, and the precise functions of these RNAs in maintaining germline genome integrity remain to be determined.

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**Fig. 3. The piRNA pathway is required for germline development.** (A) piwi is required for the self-renewing division of germline stem cells during oogenesis. DAPI-stained images of 0- to 1-day-old adult ovarioles from wild-type (WT, +/+ ) and piwi2 Drosophila. WT ovarioles contain a long string of developing egg chambers produced through continuous stem cell division. By contrast, piwi2 mutant ovarioles typically contain only two egg chambers, derived through stem cell differentiation and loss. Ge, gerarium; S1, stage 1 egg chamber [from Cox et al. (Cox et al., 1998)]]. (B) Increased DNA damage in the germline cells of aub mutant ovaries. Drosophila ovaries immunostained to reveal the phosphorylated form of histone H2Av (γ-H2Av, red) and DNA (blue). γ-H2Av accumulates near double-strand break (DSB) sites. In WT ovaries, γ-H2Av foci are restricted to region 2 of the gerarium, where meiotic DSBs form. In aub mutant ovaries, γ-H2Av foci accumulate in cells within the gerarium and persist and increase in intensity only in the germline as cysts bud from the gerarium to form egg chambers [from Klattenhoff et al. (Klattenhoff et al., 2007)]. (C) Miwi2 mutation depletes germ cell lineages in mouse testes. Hematoxylin and Eosin (HE) staining of WT and Miwi2 mutant adult testes shows germine degeneration in Miwi2 mutant mouse testes [from Carmell et al. (Carmell et al., 2007)]. (D) Zwi is necessary for the maintenance of the zebrafish germline. HE staining shows that zwi mutants have germ-cell-depleted testes, as compared with WT [from Houwing et al. (Houwing et al., 2007)]. (A) Reprinted with permission from Cold Spring Harbor Laboratory Press; (B,C,D) reprinted with permission from Elsevier.
accumulation is not a consequence of DNA damage signaling. Piwi-class Argonaute–piRNA complexes, like siRNA or miRNA-Argonaute complexes, can cleave perfectly matched RNA targets in vitro (Gunalwar et al., 2007; Lau et al., 2006; Saito et al., 2006). As noted above, miRNA-Argonaute complexes that imperfectly pair with target mRNAs induce translational silencing (Valencia-Sanchez et al., 2006). It is therefore possible that piRNA–Piwi-class-Argonaute complexes also trigger the translational silencing of imperfectly matched targets, including mRNAs from single-copy genes such as *oskar*. Consistent with this speculation, a subset of piRNAs associates with polysomes in the mouse (Grivna et al., 2006).

**Fertility and Stellate silencing in Drosophila males**

Most *Drosophila* piRNA-pathway mutations reduce male fertility (Cox et al., 1998; Schmidt et al., 1999; Stapleton et al., 2001; Tomari et al., 2004), and this is linked to the overexpression of Stellate protein. The function of Stellate is not known, but it is encoded by repeated genes on the X chromosome that are suppressed by the Y-linked *Suppressor of Stellate [Su(Ste)]* locus (Aravin et al., 2001; Livak, 1990). *Su(Ste)* consists of bi-directionally transcribed repeats that are highly homologous to *Stellate*, and deletion of the *Su(Ste)* locus leads to the massive overexpression of Stellate protein, which assembles into crystals in the testes (Bozzetti et al., 1995; Livak, 1984; Palumbo et al., 1994). piRNAs of 25 to 27 nt are produced from the *Su(Ste)* locus, and mutations in piRNA-pathway genes lead to Stellate crystal formation (Aravin et al., 2001; Pane et al., 2007; Stapleton et al., 2001; Tomari et al., 2004). piRNAs from the *Su(Ste)* locus thus silence expression of *Stellate* in trans. It is currently unclear whether this reflects transcriptional or post-transcriptional silencing. Stellate overexpression alone could induce sterility, but defects in silencing of other genes could also impact male fertility. piRNA-pathway mutations lead to mobilization of at least a subset of transposons in the male germ line (Kalmykova et al., 2005), and insertional mutations associated with transposon mobilization might also reduce male fertility.

**Male germ line development in the mouse**

The mouse genome encodes three Piwi homologs, Miwi, Miwi2 and Mili (also known as Piwi1, Piwi4 and Piwi2, respectively – Mouse Genome Informatics), and all three are expressed at high levels in testes and are required for male fertility (Aravin et al., 2006; Deng and Lin, 2002; Girard et al., 2006; Livak, 2006a; Kuramochi-Miyagawa et al., 2001; Sasaki et al., 2003). Both Mili and Miwi bind piRNAs, and knockout mutations in the *Mili* and *Miwi* genes block piRNA production (Aravin et al., 2006; Girard et al., 2006; Livak, 2006a). Single null-mutations in each of the three genes lead to male sterility (Carmell et al., 2007; Deng and Lin, 2002; Kuramochi-Miyagawa et al., 2004). Spermatogenesis in the mouse is a coordinated process that can be divided into three phases: mitosis, meiosis and spermiogenesis (de Rooij and Grootegoed, 1998). In the first phase, stem cells localized in the basal layer of the epithelium divide mitotically to self-renew and generate a population of primary spermatocytes. In the second phase, the primary spermatocytes progress through meiosis to generate haploid round-spermatids. During leptotene of meiotic prophase I, duplicated chromosomes condense and begin to pair. Pairing is completed and the synaptonemal complex forms during zygotene, and crossing over occurs in pachytene. The homologs begin to separate in diplotene and finally resolve in diakinesis. During the third phase, round spermatids mature and elongate and are then released into the lumen of the tubule. In *Mili, Miwi* and *Miwi2* mutants, the testes appear normal until about 2 weeks post-partum, which roughly corresponds with the first round of meiosis. However, post-meiotic cells do not form (Fig. 3C). Mutations in *Mili* and *Miwi2* block progression through pachytene, whereas *Miwi* mutant spermatocytes develop to the round-spermatid stage but do not complete spermiogenesis (Carmell et al., 2007; Deng and Lin, 2002; Kuramochi-Miyagawa et al., 2004). The timing of developmental arrest correlates with the temporal expression of Mili and Miwi proteins. Mili is first detected in male primordial germ cells and is present throughout pachytene, whereas Miwi is expressed only from mid-pachytene to the round-spermatid stage (Deng and Lin, 2002; Kuramochi-Miyagawa et al., 2004). The temporal expression pattern of Miwi2 during spermatogenesis has not been reported.

Mutations in each of the three genes lead to the degeneration of the male germ line, whereas somatic cells appear to remain relatively unaffected (Carmell et al., 2007; Deng and Lin, 2002; Kuramochi-Miyagawa et al., 2004) (Fig. 3C). Similar spermatogenesis-arrest phenotypes have been observed in mutants that disrupt synopsis or DNA repair (Barea et al., 2001; Barchi et al., 2005; Xu et al., 2003). Additionally, high levels of γ-H2AX staining, indicative of DNA break formation, have been observed in *Miwi2* mutants (Carmell et al., 2007). All of the above suggest that mutations in *piwi* homologs in mice, as with piRNA-pathway mutations in *Drosophila*, lead to DNA damage and to the activation of a DNA damage response, including apoptotic degeneration of germine cells.

In piRNA-pathway *Drosophila* mutants, germline DNA damage is associated with the massive overexpression of retrotransposons, and most of the piRNAs are linked to retrotransposon and repeated sequences (Brennecke et al., 2007; Klattenhoff et al., 2007; Voggin et al., 2006). These observations suggest that germline DNA damage is caused by transposon mobilization, although this has not been demonstrated (Klattenhoff et al., 2007). By contrast, the piRNAs from adult mouse testes are depleted of repeated and retrotransposon sequences (Aravin et al., 2006; Girard et al., 2006; Livak et al., 2006a). However, a recent study has identified a pre-pachytene cluster of Mili-interacting piRNAs that include a substantial number of repeat and retrotransposon sequences (Aravin et al., 2007). Moreover, *Mili* and *Miwi2* mutations in mice lead to the derepression of retrotransposon transcripts (Aravin et al., 2007; Carmell et al., 2007). The piRNA pathway might therefore have a conserved function in silencing retrotransposons and preventing DNA damage in the germ line. However, in contrast to flies, the female germ line is not affected by single mutations in mouse Piwi-class Argonaute genes (Carmell et al., 2007; Deng and Lin, 2002; Kuramochi-Miyagawa et al., 2004). This could indicate that a distinct pathway fulfills this role in the mammalian female germ line. However, the Piwi-class Argonautes could also act redundantly during oogenesis, and double or triple mutants might therefore reveal a role for piRNAs in the male mouse germ line.

**Sex determination and germ line development in zebrafish**

The zebrafish genome encodes two clear Piwi homologs, *ziwi* (also known as *piwi1* – ZFIN) and *zi* (*zi*). *Ziwi* appears to be an ortholog of the mouse Miwi protein, whereas *Zi* is more similar to mouse Mili. Only *Ziwi*, which is expressed specifically in the male and female germine cells, has been characterized (Houwing et al., 2007). *Ziwi*, like the *Drosophila* Ago3 and Aub proteins, is primarily cytoplasmic and localizes to perinuclear nuage. Strikingly, *ziwi*-null mutations also result in the apoptotic loss of germ cells from the testes (Fig. 3D). Reduced levels of *ziwi* function permit the survival of male germ cells to the adult stage, but lead to elevated levels of apoptosis...
in adult germ cells and to varying levels of infertility. piRNAs isolated from zebrafish testes and ovaries show the same molecular properties as piRNAs from other organisms, and many are derived from repetitive sequences. Mutations in zivi also affect sex determination, and all surviving mutant animals are male (Houwing et al., 2007). As a result, the role of zivi in the female germline could not be assessed. Other mutations that reduce germ cell number also lead to male development, suggesting that the sex-determination phenotype is secondary to the loss of germ cells (Slanchev et al., 2005). However, a more direct role for piRNAs in sex determination cannot be excluded.

Conclusions and open questions

In flies, fish and mice, piRNA-pathway mutations lead to germline-specific defects, and studies in Drosophila indicate that some of these defects result from DNA damage signaling. piRNAs might therefore have a conserved function in preserving germline genome integrity. In flies, piRNA mutations lead to the overexpression of retrotransposons, and retrotransposon mobilization could cause the DNA lesions that lead to germline DNA damage. However, piRNA-pathway mutations have been linked to the mobilization of a single transposon in the Drosophila male germline (Kalmykova et al., 2005), and there is no direct evidence that the breaks that accumulate in piRNA-pathway mutations in the female germline are associated with transposition events. piRNAs could therefore directly promote repair, induce the assembly of damage-resistant chromosome structures, or suppress the expression of euchromatic genes that induce DNA breaks.

The mechanism of piRNA-based gene silencing also remains to be determined. Mutations in genes involved in the piRNA pathway in Drosophila have been reported to disrupt position-effect variegation (PEV), a form of transcriptional silencing that is caused by the spreading of heterochromatin from peri-centromeric and telomeric regions (Pal-Bhadra et al., 2002; Pal-Bhadra et al., 2004). piRNAs could therefore silence gene expression by promoting heterochromatin assembly, which could directly suppress transcription. Alternatively, piRNA-Argonaute complexes could associate with heterochromatin and catalyze the co-transcriptional destruction of nascent transcripts. The latter possibility is suggested by studies in fission yeast that indicate that siRNA-containing Argonaute proteins are recruited to heterochromatic regions, where they degrade transcripts as they are produced (Verdel and Moazed, 2005). However, mouse and Drosophila Piwi-class Argonautes are also present in the cytoplasm, and piRNA–Piwi-class-Argonaute complexes could silence gene expression by targeting the destruction of mature mRNA following exit from the nucleus. It is also possible that piRNA-Argonaute complexes function in both the nucleus and cytoplasm during the development of complex multicellular organisms.

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