Soma-dependent modulations contribute to divergence of rhomboid expression during evolution of Drosophila eggshell morphology

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Patternig of the respiratory dorsal appendages (DAs) on the Drosophila melanogaster eggshell is tightly regulated by epidermal growth factor receptor (EGFR) signaling. Variation in the DA number is observed among Drosophila species; D. melanogaster has two DAs and D. virilis has four. Diversification in the expression pattern of rhomboid (rho), which activates EGFR signaling in somatic follicle cells, could cause the evolutionary divergence of DA numbers. Here we identified a cis-regulatory element of rho. A comparison with D. melanogaster rho enhancer and activity studies in homologous and heterologous species suggested that these rho enhancers did not functionally diverge significantly during the evolution of these species. Experiments using chimeric eggs composed of a D. virilis oocyte and D. melanogaster follicle cells showed the evolution of DA number was not attributable to germline Gurken (Grk) signaling, but to divergence in events downstream of Grk signaling affecting the rho enhancer activity in somatic follicle cells. We found that a transcription factor, Mirror, which activates rho, could be one of these downstream factors. Thus, evolution of the trans-regulatory environment that controls rho expression in somatic follicle cells could be a major contributor to the evolutionary changes in DA number.

KEY WORDS: Drosophila melanogaster, Drosophila virilis, rhomboid, mirror, gurken, Broad-Complex, EGFR signaling, cis-regulatory element, trans-regulatory landscape, Evolution, Eggshell, Dorsal appendage

INTRODUCTION

Evolutionary changes in gene regulation are a major cause of the diversification of morphological traits in animals (Carroll et al., 2001; Davidson, 2001; Simpson, 2002). Although differences in the expression patterns of genes with instructive roles in morphogenesis have been demonstrated in various species (Averof and Patel, 1997; Gompel and Carroll, 2003; Shapiro et al., 2004; Simpson et al., 1999; Stern, 1998), few studies have addressed the molecular mechanisms underlying the diversification of these gene expression patterns (Belting et al., 1998; Gompel et al., 2005; Wittkopp et al., 2002). The dorsal appendages (DAs) are specialized respiratory structures on the drosophilid eggshell (Hinton, 1969; Spradling, 1993a). The mechanisms of their morphogenesis have been extensively studied in Drosophila melanogaster, whose eggshell has two DAs (Fig. 1B) (Berg, 2005). There is remarkable diversity in the DA morphology among species, including their size, shape and number, although these characteristics are stereotyped within each species (Kambysellis and Craddock, 1997; Patterson and Stone, 1952; Throckmorton, 1962). Thus, comparative studies of gene expression patterns during DA formation are useful for understanding the mechanisms underlying the evolutionary diversification of gene expression (Barkai and Shilo, 2002; Derheimer et al., 2004; James and Berg, 2003; Nakamura and Matsuno, 2003; Peri et al., 1999; Perrimon and Duffy, 1998). The egg chamber of Drosophila consists of a single oocyte and 15 nurse cells surrounded by a layer of somatic follicle cells (Margolis and Spradling, 1995; Spradling, 1993a). In D. melanogaster, the DA primordia arise from a subset of follicle cells that are specified by epidermal growth factor receptor (EGFR) signaling (Nilson and Schupbach, 1999; Wasserman and Freeman, 1998). Gurken (Grk) is a transforming growth factor-α-like protein and an oocyte-specific ligand for EGFR that localizes to the dorsal-anterior end of the oocyte and is presented to the overlying follicle cells (Neuman-Silberberg and Schupbach, 1993; Nilson and Schupbach, 1999; Wasserman and Freeman, 1998). Grk induces the expression of rhomboid (rho), which encodes a serine protease, in a single population of dorsal anterior follicle cells (Lee et al., 2001; Ruohola-Baker et al., 1993; Urban et al., 2001), and the Decapentaplegic signaling pathway helps limit the expression of rho in these cells (Peri and Roth, 2000). In these follicle cells, Rho processes Spitz, a transmembrane ligand for EGFR, to a secreted and active form, which in turn amplifies EGFR signaling in the follicle cells (Sapir et al., 1998; Schweitzer et al., 1995; Wasserman and Freeman, 1998). The high EGFR signaling activity triggers the expression of argos at the dorsal anterior midline and subsequently establishes a negative feedback loop, resolving the single peak of EGFR signaling into twin peaks (Wasserman and Freeman, 1998). Consequently, a single DA primordium is formed at each region of peak EGFR signaling activity (Wasserman and Freeman, 1998).

D. virilis, a species that diverged from D. melanogaster 40–60 million years ago, has four DAs (Fig. 1A,C) (Powell, 1997). We previously showed that rho is expressed differently between D. melanogaster and D. virilis (Fig. 1D,E). At stage 10A, rho is expressed in D. melanogaster in a dorsal anterior saddle-shaped zone that includes the midline (Fig. 1D), but in D. virilis there are two dorsal-lateral domains (Fig. 1E). At stage 10B, rho expression is refined into two L-shaped stripes in D. melanogaster (Fig. 1D);...
the pattern in *D. virilis* becomes a V-shaped stripe with its apex missing (Fig. 1E). Finally, the *rho* expression is maintained in two regions of follicle cells where the two DAs will form in *D. melanogaster* at stage 12 (Fig. 1D), whereas in *D. virilis*, *rho* expression is restricted to four domains corresponding to the positions of the future DAs (Fig. 1E). Thus, changes in the regulation of *rho* expression could be responsible for the divergence in DA number (Nakamura and Matsuno, 2003). In this study, we investigated the mechanisms by which *rho* expression diverged during the evolution of *D. melanogaster* and *D. virilis*. Our results suggest that divergence of the trans-acting landscape regulating the *rho* expression probably had a crucial role in the evolution of different DA numbers in these two species.

**MATERIALS AND METHODS**

**Drosophila strains**

The *Drosophila* strains used as wild type were: *D. melanogaster*, Canton-S; *D. virilis*, stocks #15010-1051.0 and #15010-1051.87 (Tucson *Drosophila* Stock Center, http://stockcenter.arl.arizona.edu). The *D. melanogaster* *yw* and *D. virilis* *w* (stock #15010-1051.53, *white* mutant) strains were used as the *D. melanogaster* and *D. virilis* transformation hosts, respectively. The *D. melanogaster* EGFP-Vasa strain (Sano et al., 2002) was used as a pole cell transplantation host.

**Immunohistochemistry**

Immunofluorescent staining of ovaries was performed as described (James and Berg, 2003), except that Block Ace (Dainippon Pharmaceutical) was used as a blocking reagent. The following primary antibodies were used: rabbit anti-green fluorescent protein (GFP) (1:1000, MBL), mouse anti-β-galactosidase (Gαl) (1:500, Promega) and rabbit anti-Broad-Complex (BR-C) core (1:2000) (Dequier et al., 2001). Alexa Fluor-488-conjugated anti-rabbit immunoglobulin G (IgG) (1:400, Molecular Probes) and Cy3-conjugated anti-mouse IgG (1:400, Rockland) were used as secondary antibodies. Immunofluorescent staining of embryos was performed as described (Hayashi et al., 2004). Embryos were stained with rabbit anti-Vasa (1:500) and mouse anti-GFP (1:500, Wako Pure Chemicals) antibodies, and then treated with Alexa Fluor-568-conjugated anti-rabbit IgG (1:500, Molecular Probes) and Alexa Fluor-488-conjugated anti-mouse IgG (1:500, Molecular Probes).

**In situ hybridization**

The RNA probes were labeled with digoxigenin (Roche), and in situ hybridization was performed as described (Wasserman and Freeman, 1998).

**Cloning of mirror (mirr)**

Partial DNA fragments of *mirr* for in situ hybridization were amplified using genomic DNAs from *Canton-S* and *D. virilis* (#15010-1051.87) as template DNAs by PCR. The primers were: *Mrr_FW, 5'-GATATGATGACCGACC-3'* and *Mrr_RV, 5'-CCTATAAAGCTTGTAGTCG-3'*.

**Cloning of the *D. virilis* 5′ rho regulatory DNA**

The DNA probe of the *D. virilis* rho cDNA was labeled with digoxigenin (DIG DNA labeling Mix, Roche) by random-primed labeling (Nakamura and Matsuno, 2003). A *D. virilis* phage genomic library (gift of T. C. Kaufman, Indiana University, Bloomington, IN) was screened with this probe using standard conditions (Sambrook and Russel, 2001). Twenty-one overlapping phage clones that hybridized with the *D. virilis* rho probe were isolated. The three largest genomic fragments isolated from these phage clones were digested with *SalI* and subcloned into the *SalI* site of pBlueScript KS(−). These subclones were sequenced, aligned and ligated. Finally, a genomic DNA fragment 12-kb upstream of the start site of the *D. virilis* rho cDNA was obtained (GenBank accession number AB278158).

**Transgene construction for rho enhancer analysis**

A genomic fragment covering the 2.2-kb upstream region of the *D. melanogaster* rho gene was generated by PCR using the *D. melanogaster* genomic PI clone DS02734 (GenBank accession number AC004343) as a template (Kimmerly et al., 1996), and subcloned into the *BanHI* site of pCaSpeR-NLStacZ (gift of C. Thummel, Howard Hughes Medical Institute, University of Utah, Salt Lake City, UT). The primers were: *rho2.2-FW, 5'-CGGGATCCCGCAAAGTCATTTTCTGTC-3'* and *rho2.2-RV, 5'-CGGGATCCGTTTCTGCTGTGACCC-3* (Restriction enzyme cloning sites are underlined.)

The 2.2-kb upstream fragment of the *D. melanogaster* rho gene and fragments containing the 4.2- and 12-kb upstream regions of the *D. virilis* rho gene were subcloned into the *BamHI* and *KpnI/BamHI* sites of pSL(bsp27mp-NLS-EGFP) (T.N., unpublished), respectively. The resulting constructs were digested with *AscI*, and each insert was cloned into the *AscI* site of pBac[3xP3-DsRedaf].

**Transformation of *D. melanogaster* and *D. virilis***

Germline transformation of the P-element CaSpeR vectors was performed according to a standard protocol (Spradling, 1993b). For transformation with the piggyBac vector, piggyBac constructs were co-injected into the eggs of *D. melanogaster* *yw* and *D. virilis* *w* with *psp*-pBac, and flies were screened for 3xP3-DsRed expression under a fluorescence stereoscopic microscope (gift of E. A. Wimmer, Georg August University, Göttingen, Germany). For each transgene, at least three independent insertions were isolated and characterized.

**Pole cell transplantation**

Pole cell transplantation was performed as described (Kobayashi et al., 1996), with the following modifications. As a marker for the *D. melanogaster* germline, we used an EGFP-vasa construct that expresses GFP specifically and continuously in the germline throughout the life cycle (Sano et al., 2002). We transplanted pole cells from *D. virilis* (#15010-1051.0) embryos [200-250 minutes after egg laying (AEL) (25°C)] into *D. melanogaster* embryos [100-150 minutes AEL (25°C)] carrying the EGFP-vasa. The donor embryos were at the cellular blastodermal stage.

**RESULTS**

**Identification of the *D. virilis* rho enhancer responsible for rho expression in the DA-forming follicle cells**

In *D. melanogaster*, a region of the *rho* gene 2.2-kb upstream of its transcriptional start site contains a cis-regulatory element that is responsible for its expression during oogenesis (Dorman et al., 2004; Ip et al., 1992; Sapir et al., 1998; Ward and Berg, 2005). This *rho* enhancer, termed Dmel rho2.2, is sufficient to drive the expression of a reporter gene in the developing follicle cells (Dorman et al., 2004; Sapir et al., 1998; Ward and Berg, 2005). At stage 10B, Dmel rho2.2 is activated in L-shaped stripes on either side of the midline (Dorman et al., 2004; Sapir et al., 1998; Ward and Berg, 2005). This expression pattern resembles that of endogenous *rho*, which is essential for DA formation, at the same stage (Fig. 1D and Fig. 3C) (Dorman et al., 2004; Sapir et al., 1998).

We speculated that a similar cis-regulatory element should exist in the *D. virilis* *rho* gene. Therefore, we isolated a 12-kb genomic region upstream of the *D. virilis* rho cDNA start site (GenBank accession number AB278158). To test whether the 12-kb fragment or a 4.2-kb upstream fragment derived from it contained a regulatory sequence that governs *rho* expression in the follicle cells, we analyzed the activity of these fragments in *D. virilis* using piggyBac-mediated transgenesis (Handler, 2002). When placed upstream of a GFP reporter gene, the 12- and 4.2-kb upstream fragments drove reporter expression in the follicle cells of *D. virilis* during DA formation in essentially the same manner (Fig. 2 and data not shown). Therefore, we used the 4.2-kb fragment in the following studies, because a shorter fragment is preferable for generating transgenic lines efficiently in *D. virilis* and *D. melanogaster*. At stage 10B, Dvir rho4.2 drove reporter expression in a pattern identical to the distribution of endogenous *D. virilis* rho mRNA (Fig. 2A, C). At stage 12, Dvir rho4.2 also drove GFP expression in the four
Fig. 1. Evolutionary divergence of eggshell morphology and rho expression pattern between D. melanogaster and D. virilis. (A) The egg of D. virilis has four DAs, an ancestral trait, as found in the Hirtodrosophila outgroup of the genus Drosophila. The two DAs found in D. melanogaster is a more recently evolved trait. D. virilis and D. melanogaster diverged 40-60 million years ago (mya). (B,C) The eggshells of D. melanogaster (B) and D. virilis (C) are shown with anterior to the left (dorsal view). (D,E) Schematic comparison of the rho expression patterns between D. melanogaster and D. virilis during oogenesis. Dorsal lateral views of stage 10A- to 12-egg chambers are shown with rho expression (blue). Anterior is to the left. (D) D. melanogaster rho was expressed in a saddle-shaped zone at the dorsal anterior at stage 10A. This expression was retrained into an L-shaped stripe on either side of the dorsal midline at stage 10B. Expression was then restricted to the anterior row lacking the midline region at stage 11, as it continued until stage 12. (E) D. virilis rho was expressed in two domains at the dorsal-lateral sides at stage 10A. No expression occurred in the midline, unlike in D. melanogaster. The expression was retrained at the posterior region and refined into a V-shaped stripe missing its apex at stage 10B. Expression was upregulated at the front and rear of each stripe, and expression in the rear moved anteriorly at stage 11. Subsequently, the expression was divided into four domains at stage 12, corresponding to the positions of the four DAs.

domains that subsequently form the four DAs (Fig. 2D); this pattern was also similar to that of endogenous rho at the same stage (Fig. 2B). We concluded that Dvir rho4.2 consists of an enhancer orthologous to Dmel rho2.2.

Broad-Complex (BR-C) is expressed in the presumptive DA-forming cells (Deng and Bownes, 1997; Tzolovsky et al., 1999). The juxtaposition of rho-expressing and BR-C-expressing cells is required for DA formation in D. melanogaster (Ward and Berg, 2005). In cells expressing rho, Spitz is converted into an active and secreted ligand for EGFR (Lee et al., 2001; Urban et al., 2001), so that EGFR signaling is activated and triggers the expression of BR-C in adjacent cells (Schweitzer et al., 1995; Ward and Berg, 2005). In D. virilis and D. melanogaster, the rho and BR-C expression domains are mutually exclusive at stage 10B (Nakamura and Matsuno, 2003), indicating that the genetic cascade involving rho and BR-C is conserved between these species. To test whether Dvir rho4.2 carries sufficient information to restrict its activation anterior to the BR-C-expressing domain, we analyzed the expression of Dvir rho4.2-GFP and BR-C in D. virilis. Dvir rho4.2 was activated in a single row of cells anterior and adjacent to BR-C-expressing cells (Fig. 2E-G). These results suggested that Dvir rho4.2 contains sufficient information for comparative studies with Dmel rho2.2 in these two species.

Changes in the trans-regulatory landscape could cause the evolutionary divergence in rho expression

Phylogenetic analyses indicated that four-DA eggs are ancestral compared with two-DA eggs (Fig. 1A) (Powell, 1997; Throckmorton, 1962). This suggests that changes occurred in the trans-acting landscape regulating the cis-regulatory elements of rho and/or in these cis-regulatory elements themselves during the evolution from the four- to two-DA eggs. We assumed that if divergence of the trans-regulatory landscape was wholly responsible for the species-specific expression patterns of rho, the exogenous rho enhancers would adopt the same expression pattern as the endogenous rho expression (i.e. in D. virilis, Dmel rho2.2 should be activated in a similar pattern to Dvir rho4.2). By contrast, if evolutionary modifications of the cis-regulatory elements were responsible for the divergence in rho expression, the activation patterns of Dvir rho4.2 and Dmel rho2.2 in the heterologous species should match the expression pattern of the endogenous rho in their species of origin (i.e. their homologous species).

To address this issue, we introduced the Dmel rho2.2-GFP reporter construct into D. virilis. As reported previously, Dmel rho2.2 was activated in L-shaped domains at stages 10B and 12 in D. melanogaster (Dorman et al., 2004). Interestingly, Dmel rho2.2 was activated in the V-shape with its apex missing in D. virilis at stage 10B (Fig. 3A). This pattern was very similar to the expression patterns of Dvir rho4.2-GFP and the endogenous rho in D. virilis at this stage. Furthermore, at stage 12, Dmel rho2.2 drove expression in a pattern resembling that of Dvir rho4.2-GFP and endogenous rho in D. virilis, which was significantly different from the activation pattern of the Dmel rho2.2 in its homologous species, D.
Our results suggested that the trans-regulatory landscapes that direct rho expression are evolutionarily divergent between D. virilis and D. melanogaster. However, we also noted that the expression domain of the Dvir rho\textsuperscript{4,2}-GFP was slightly expanded posteriorly compared with that of the Dmel rho\textsuperscript{2,2}-GFP in D. melanogaster (compare Fig. 3E with Fig. 3C). This difference became more obvious at stage 12 (compare Fig. 3F with Fig. 3D). At this stage, the Dvir rho\textsuperscript{4,2}-GFP was expressed in a square on either side of the midline, rather than in the L-shaped pattern (Fig. 3F).

To study further the differential activation patterns between Dvir rho\textsuperscript{4,2} and Dmel rho\textsuperscript{2,2} in D. melanogaster, we introduced Dvir rho\textsuperscript{4,2}-GFP and Dmel rho\textsuperscript{2,2}-\beta-Gal simultaneously into D. melanogaster, and observed the expression patterns driven by Dvir rho\textsuperscript{4,2} and Dmel rho\textsuperscript{2,2} with anti-GFP and anti-\beta-Gal antibody staining, respectively. Both the GFP and \beta-Gal products of the reporter constructs carry a nuclear localization signal. Thus, the expression of these reporters was detected as nuclear staining at the single-cell level. The expression of Dvir rho\textsuperscript{4,2}-GFP and Dmel rho\textsuperscript{2,2}-\beta-Gal differed temporally and spatially (Fig. 4). When Dmel rho\textsuperscript{2,2}-\beta-Gal expression started, early in stage 10B, the Dvir rho\textsuperscript{4,2}-GFP expression was not yet detectable (Fig. 4A-C). This difference was not owing to features of the GFP and \beta-Gal reporters (for example, their relative translational efficiencies), because when the GFP and \beta-Gal reporters were expressed under the control of the same enhancer, Dmel rho\textsuperscript{2,2}, their expression patterns were essentially identical, temporally and spatially (see Fig. S1 in the supplementary material). Late in stage 10B, both Dvir rho\textsuperscript{4,2}-GFP and Dmel rho\textsuperscript{2,2}-\beta-Gal were detectable (Fig. 4D-F). The anterior border of the expression domain of Dvir rho\textsuperscript{4,2}-GFP and Dmel rho\textsuperscript{2,2}-\beta-Gal was the same (Fig. 4F). However, whereas Dmel rho\textsuperscript{2,2}-\beta-Gal was expressed in a single row of cells (Fig. 4D), Dvir rho\textsuperscript{4,2}-GFP was expressed in one or two extra rows posterior to the single row where both reporters were expressed (Fig. 4E). At stage 12, expression of the Dmel rho\textsuperscript{2,2}-\beta-Gal was still restricted to the single row of cells (Fig. 4G), whereas the expression domain of the Dvir rho\textsuperscript{4,2}-GFP had expanded posteriorly (Fig. 4H). These results suggest that the functions of the rho enhancers also evolved between these two species, although both enhancers maintained the ability to respond to the positional information that defines the anterior borders of their activation. However, we also noted that a few of the anterior-most cells expressed Dvir rho\textsuperscript{4,2}-GFP but not Dmel rho\textsuperscript{2,2}-\beta-Gal at stage 12 (Fig. 4I), suggesting that some other functions might have also changed between the two enhancers.

**Conservation of the Grk signal during evolution of the DA number**

During DA patterning, the germline oocyte provides positional information to the somatic follicle cells through the Grk signal (Nilson and Schupbach, 1999). A mathematical model predicts that the distribution and amounts of Grk could play a key role in determining the number of DAs (Shvartsman et al., 2002). Considering that the Grk signal serves as the first cue for the
position information that defines the expression patterns of rho in the follicle cells, we proposed the following two hypotheses: first, that some divergence in the pivotal mechanism for determining the number of DAs occurred in the Grk signal itself, and second, that the trans-regulatory landscape that modifies the Grk signal in somatic pole cells expressed only Vasa (B, green) and Dvir rho4.2-GFP (H) largely overlapped with that of Dmel rho2.2-β-Gal (G) and Dvir rho4.2-GFP (H) activation domains were similar, but the posterior expansion of Dvir rho4.2-GFP expression became prominent (I). The right panels are merged images of the left and middle panels.

Fig. 4. Function of the rho enhancer also diverged between D. melanogaster and D. virilis. (A-I) D. melanogaster transgenic flies carrying both Dmel rho2.2-β-Gal (magenta in A,C,D,F,G,I) and Dvir rho4.2-GFP (green in B,C,E,F,H,I) reporters were generated. The activities of the two enhancers were then determined at different developmental stages: early in stage 10B (A-C), late in stage 10B (D-F) and stage 12 (G-I). (A-C) At early stage 10B, Dmel rho2.2-β-Gal (A) was activated, but Dvir rho4.2-GFP (B) was not yet active (C). (D-F) Late in stage 10B, Dvir rho4.2-GFP expression began (E) in a pattern similar to that of Dmel rho2.2-β-Gal (D). The domain of Dvir rho4.2-GFP activation (E) largely overlapped with that of Dmel rho2.2-β-Gal (D), although a slight posterior expansion of Dvir rho4.2-GFP was seen (F). (G-I) The anterior boundaries of the Dmel rho2.2-β-Gal (G) and Dvir rho4.2-GFP (H) activation domains were similar, but the posterior expansion of Dvir rho4.2-GFP expression became prominent (I). The right panels are merged images of the left and middle panels.

Fig. 5. Conservation of the Grk signal in D. melanogaster and D. virilis. (A) The experimental scheme for interspecific pole cell transplantation from D. virilis to D. melanogaster embryos. (Top) Pole cells were transplanted from D. virilis donor embryos into D. melanogaster host embryos carrying the EGFP-vasa construct. (Bottom) Left: a normal egg chamber composed of an EGFP-vasa-positive D. melanogaster oocyte and D. melanogaster somatic follicle cells. The D. melanogaster Grk activated D. melanogaster EGFR in this egg chamber. Right: a chimeric egg chamber. In the egg chamber of a D. melanogaster host female, the oocyte was replaced with one of D. virilis origin. In this chimeric egg chamber, the D. virilis Grk activated the D. melanogaster EGFR and directed the DA formation. (B-B′) A gonad of a D. melanogaster host embryo with transplanted D. virilis pole cells. The host embryos were stained with anti-EGFP (B, green) and anti-Vasa (B′, magenta) antibodies. The D. melanogaster host pole cells expressed both GFP and Vasa (B, green; B′, white), whereas the transplanted D. virilis pole cells expressed only Vasa (B′, magenta). The D. virilis pole cells were located within the gonad of the D. melanogaster host (B′, magenta). B′ is a merged image of B and B′. (C) Ovary of a D. melanogaster host female. GFP-positive host germline (green) and GFP-negative D. virilis germline (white arrowhead) cells are shown. The D. virilis germline was surrounded by D. melanogaster host follicle cells. (D,E) The chimeric egg (negative for EGFP, data not shown) had two DAs (E) identical to those of the wild-type egg (D). (F,G) The percentages of eggs in which the DA roots were separated by the distances indicated in the horizontal axes are shown. The two DAs were separated by a mean distance of 48.2±4.6 μm (n=57) in the wild-type (F) and 49.2±3.6 μm (n=12) in the chimeric (G) eggshells. The differences were not significant (0.5>p>0.2, Student’s t-test).
First, we examined whether the *D. virilis* pole cells could enter the gonad of the *D. melanogaster* embryo and whether the *D. virilis* germline cells could form the chimeric egg chamber in concert with *D. melanogaster* follicle cells in *D. melanogaster* ovaries (Fig. 5B-C). The transplanted *D. virilis* pole cells, which expressed only endogenous Vasa (Fig. 5B, purple), were incorporated into the gonad of *D. melanogaster* together with the *D. melanogaster* pole cells (Fig. 5B). Furthermore, these germine cells derived from *D. virilis* formed a chimeric egg chamber together with the *D. melanogaster* follicle cells (white arrowhead in Fig. 5C), despite their phylogenetic divergence. In contrast to the prediction from the mathematical model, we found that all the chimeric eggs (n=16) observed in four host females had two DAs (Fig. 5E), identical to the pattern of *D. melanogaster* (Fig. 5D).

This result suggests that the germline Grk signal did not change significantly during the evolution from four- to two-DA eggs. However, this interspecific transplantation could have introduced a non-specific effect that allowed the chimeric egg to develop two DAs, even if the Grk signal had diversified between the two species. For example, an incompatibility between the *D. virilis* Grk and the *D. melanogaster* EGFR could compensate for a difference in Grk signals. To address this problem, we took advantage of the fact that the Grk signal has two roles during oogenesis (Nilson and Schupbach, 1999). In addition to its role in DA formation, the Grk signal has an essential role in the dorsal-ventral patterning of the egg (Neuman-Silberberg and Schupbach, 1993; Nilson and Schupbach, 1999). When the dorsal-ventral patterning is aberrant in *D. melanogaster*, the DAs are shifted with respect to the dorsal midline, dorsally or ventrally, respectively, with the loss or gain of Grk signaling (Neuman-Silberberg and Schupbach, 1993; Nilson and Schupbach, 1999). Therefore, we measured the distance between the roots of the two DAs in wild-type and chimeric eggshells, both of which were laid by a single transplanted host female to avoid any other effects, such as nutritional status. The distances between the two DAs in the wild-type (48.2±4.6 μm, n=57) and chimeric (49.2±3.6 μm, n=12) eggshells showed no statistically significant difference (Fig. 5F,G, 0.5>P>0.2, Student’s t-test), suggesting that the dorsal-ventral patterning occurred normally in the chimeric eggs. It is unlikely that the two different patterning events, DA formation and dorsal-ventral patterning, both of which are triggered by Grk signal-dependent positional information, were both properly compensated for by chance. Thus, we speculate that the role of Grk in DA patterning is conserved between *D. virilis* and *D. melanogaster*, suggesting that subsequent events, downstream of the Grk signal, diverged to elicit the different expression of rho between these two species.

**Mrr is a candidate molecule responsible for the divergence of rho expression**

In *D. melanogaster*, *mrr*, which encodes a homeobox transcription factor, is expressed in dorsal anterior follicle cells (Jordan et al., 2000; Zhao et al., 2000). This expression pattern depends on the Grk signal, and *mrr* subsequently activates the expression of rho during oogenesis (Jordan et al., 2000; Jordan et al., 2005; Zhao et al., 2000). Therefore, *mrr* might introduce the evolutionary changes into the landscape of trans-regulatory factors that are responsible for the divergence of rho expression in *D. virilis* and *D. melanogaster*. To test this hypothesis, we analyzed the *mrr* expression patterns in these two species.

In both species, *mrr* expression began similarly, at the dorsal-anterior region of the follicle cells, at stage 9, prior to the onset of rho expression (Fig. 6A,E). After this stage, the *mrr* expression followed species-specific patterns, which resembled the rho expression pattern in each species. In *D. melanogaster*, the expression of *mrr* was repressed in the dorsal midline at stage 10A (white arrowhead in Fig. 6B) and was elevated in the follicle cells at the anterior boundary (white arrow in Fig. 6B), which corresponded to the anterior row of rho-expressing cells in the L-shaped pattern at stage 10B (Fig. 1D). This anterior expression continued until stage 10B (white arrow in Fig. 6C). By contrast, early in stage 10A in *D. virilis*, the *mrr* expression was repressed only at the dorsal-anterior region, not the entire dorsal midline (white arrowhead in Fig. 6F). Late in stage 10A, the region lacking *mrr* expression expanded and became a triangle (Fig. 6G), which consequently divided the *mrr*-expressing region into two dorsal-lateral domains that were reminiscent of the rho-expressing domains of *D. virilis* at stage 10A (Fig. 1E). After stage 10B, the expression of *mrr* was barely detectable in either species (Fig. 6D,H). The expression of *D. virilis* *mrr* was not restricted to the domains expressing rho (Fig. 1E). Therefore, the expression of *mrr* does not always cause the expression of rho. Nevertheless, our results suggest evolutionary changes in the *mrr* expression patterns as a candidate mechanism for the divergence of rho expression at stage 10A in *D. virilis* and *D. melanogaster*. 
DISCUSSION
Role of the trans-regulatory landscape in the evolutionary diversification of DA numbers

Changes in gene expression patterns during evolution can be attributed to two distinct mechanisms. First, alterations in the cis-regulatory sequence of a gene can be responsible for the divergence of its expression pattern. Second, changes in trans-regulatory factors can cause gene expression patterns to diverge, even if the cis-regulatory elements of these genes are conserved during evolution. Diversification in enhancer elements is known to contribute predominantly to the evolution of animal morphology (Belting et al., 1998; Gompel et al., 2005; Wittkopp et al., 2002). The gain and loss of cis-acting elements have played central roles in the divergence of the expression patterns of genes that play crucial roles in the generation of specific characteristics in different species (Gompel et al., 2005). In this study, we investigated the contribution of these two processes to the evolutionary diversification of DA numbers in D. virilis and D. melanogaster. In addition to the importance of cis-regulatory elements demonstrated previously, our findings suggest that the landscape of trans-regulatory factors could also change and affect morphological divergence during evolution.

In D. melanogaster, rho expression has an instructive role in defining the pattern of DA precursor cell formation (Sapir et al., 1998; Ward and Berg, 2005). In addition, we previously demonstrated that the expression patterns of rho diverged and were correlated with the position and number of DAs in D. virilis and D. melanogaster (Nakamura and Matsuno, 2003). Therefore, in this study, we mostly focused on the enhancers of rho in these species. To distinguish whether divergence in the trans-regulatory landscape or the cis-regulatory elements is important for the evolutionary change in rho expression patterns between D. melanogaster and D. virilis, we introduced reporter constructs of Dvir rho\(^{4.2}\) and Dmel rho\(^{2.2}\) into these two species. Phylogenetic analyses of Drosophila species suggest that the four DAs are an ancestral characteristic, and that the flies with two DAs evolved from four-DA ancestors (Fig. 1). Thus, the characteristics of Dmel rho\(^{2.2}\) were probably derived from the ancestral Dvir rho\(^{3.2}\) enhancer. We found that Dvir rho\(^{4.2}\) and Dmel rho\(^{2.2}\) adopted the expression pattern of the endogenous rho of the heterologous species. These results suggest that Dvir rho\(^{4.2}\) and Dmel rho\(^{2.2}\) did not diverge in terms of their ability to respond to the trans-acting factors in follicle cells. Therefore, we speculated that changes in the cis-regulatory elements from Dvir rho\(^{4.2}\) to Dmel rho\(^{2.2}\) were not the main cause for divergence in the activation patterns of these enhancers in their homologous species.

Although the DNA sequences of Dvir rho\(^{4.2}\) and Dmel rho\(^{2.2}\) diverged drastically, several putative binding sites for transcription factors, such as ETS, Su(H) and BR-C, were common to both (data not shown), which could explain the conserved function of the two enhancers. Recently, it was reported that BR-C represses the activity of Dmel rho\(^{2.2}\) in a cell-autonomous manner during DA patterning (Ward et al., 2006), and this repression allows the enhancer to be activated in the L-shaped pattern at stage 10B. However, Dvir rho\(^{4.2}\) was activated in one or two extra rows of cells posterior to the single row of cells where Dmel rho\(^{2.2}\) was active at this stage. At stage 12, Dvir rho\(^{4.2}\) was activated much more posteriorly, although Dmel rho\(^{2.2}\) was still active only in the single row of cells. Given that Dvir rho\(^{4.2}\) is ancestral to Dmel rho\(^{2.2}\), we speculate that Dmel rho\(^{2.2}\) lost a cis-acting element capable of being activated in this posterior region, or gained a cis-acting element that suppresses its activity in this region at stage 12. Indeed, it is likely that this posterior activation of rho is an ancestral characteristic, because the endogenous expression of rho in this region is found in D. virilis but not D. melanogaster.

Changes in cis-acting elements may contribute to the evolutionary divergence in rho expression between D. melanogaster and D. virilis

Our present analysis revealed that the functions of Dvir rho\(^{4.2}\) and Dmel rho\(^{2.2}\) are largely conserved. However, we also found that Dmel rho\(^{2.2}\) had evolved a novel trait during its diversification from Dvir rho\(^{4.2}\). In D. melanogaster, both Dvir rho\(^{4.2}\) and Dmel rho\(^{2.2}\) were activated in the L-shaped pattern at stage 10B. However, Dvir rho\(^{4.2}\) was activated in one or two extra rows of cells posterior to the single row of cells where Dmel rho\(^{2.2}\) was active at this stage. At stage 12, Dvir rho\(^{4.2}\) was activated much more posteriorly, although Dmel rho\(^{2.2}\) was still active only in the single row of cells. Given that Dvir rho\(^{4.2}\) is ancestral to Dmel rho\(^{2.2}\), we speculate that Dmel rho\(^{2.2}\) lost a cis-acting element capable of being activated in this posterior region, or gained a cis-acting element that suppresses its activity in this region at stage 12. Indeed, it is likely that this posterior activation of rho is an ancestral characteristic, because the endogenous expression of rho in this region is found in D. virilis but not D. melanogaster.

The Grk signal may not play a crucial role in the evolution of DA number in D. melanogaster and D. virilis

For the formation of DAs, the patterning of EGFR signaling activity in the follicle cells plays crucial roles in D. melanogaster (Wasserman and Freeman, 1998). Two major events are involved in the regulation of EGFR signaling activity in these cells. First, Grk specifically localizes to the dorsal anterior part of the oocyte and activates EGFR in the overlying follicle cells (Wasserman and Freeman, 1998). Second, in the follicle cells, positive and negative feedback loops elaborate the pattern of EGFR signaling activity that
ultimately determines the number of DAs (Wasserman and Freeman, 1998). Thus, the first and second events are germ- and soma-derived events, respectively.

As predicted from the above model, the intensity of Grk expression and the width of its expression domain in the oocyte are thought to determine the number of DAs (Shvartsman et al., 2002). A mathematical study predicted that changes in the amount and distribution of Grk protein in the oocyte can account for the evolution of eggshells with zero to four DAs in *Drosophila* species (Shvartsman et al., 2002). However, our experiments involving a chimeric egg chamber suggest that changes in the follicle cells, but not in the oocyte, have an instructive role in determining the number of DAs. These results suggest that the change in Grk signaling did not contribute to the evolution of DA numbers in these species. This is consistent with the previous finding that the distribution and amount of grk mRNA do not show a significant difference between *D. melanogaster* and *D. virilis* (Peri et al., 1999). However, our results do not exclude the possibility that changes in Grk signaling play major roles in the diversification of DA numbers during the evolution of other *Drosophila* species.

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**Supplementary material**

Supplementary material for this article is available at http://dev.biologists.org/cgi/content/full/134/8/1529/DC1

**References**


Evolution of *Drosophila* egg shape


