Abelson kinase regulates epithelial morphogenesis in Drosophila

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Activation of the nonreceptor tyrosine kinase Abelson (Abl) contributes to the development of leukemia, but the complex roles of Abl in normal development are not fully understood. Drosophila Abl links neural axon guidance receptors to the cytoskeleton. Here we report a novel role for Drosophila Abl in epithelial cells, where it is critical for morphogenesis. Embryos completely lacking both maternal and zygotic Abl die with defects in several morphogenetic processes requiring cell shape changes and cell migration. We describe the cellular defects that underlie these problems, focusing on dorsal closure as an example. Further, we show that the Abl target Enabled (Ena), a modulator of actin dynamics, is involved with Abl in morphogenesis. We find that Ena localizes to adherens junctions of most epithelial cells, and that it genetically interacts with the adherens junction protein Armadillo (Arm) during morphogenesis. The defects of abl mutants are strongly enhanced by heterozygosity for shotgun, which encodes DE-cadherin. Finally, loss of Abl reduces Arm and a-catenin accumulation in adherens junctions, while having little or no effect on other components of the cytoskeleton or cell polarity machinery. We discuss possible models for Abl function during epithelial morphogenesis in light of these data.

Introduction

The nonreceptor tyrosine-kinase Abl is the cellular homologue of v-abl, the transforming gene of Abelson (Abl)* murine leukemia virus (for review see Zou and Calame, 1999; Mauro and Druker, 2001). Bcr-Abl, an activated, chimeric form of Abl resulting from a chromosomal translocation, plays a causative role in human chronic myelogenous and acute lymphocytic leukemia. Bcr-Abl has deregulated tyrosine kinase activity, and an inhibitor of this kinase has shown promise in treating leukemia. Multiple substrates for oncogenic Abl kinase in diverse signaling pathways have been identified, revealing complex effects of Abl misregulation. Abl’s normal role has remained more elusive. Abl homologues are found in all animals. All share conserved NH2-terminal SH3, SH2, and tyrosine kinase domains, as well as distinct COOH-terminal F- and G-actin binding domains (for review see Lanier and Gertler, 2000). Mammalian Abl, unlike its fly homologue, also contains nuclear import and export signals and a COOH-terminal DNA binding domain, and thus it localizes to both nuclei and the cytoplasm. In nuclei, it is thought to regulate the cell cycle and the response to DNA damage (for review see Van Etten, 1999). Cytoplasmic Abl predominantly associates with the actin cytoskeleton (e.g., van Etten et al., 1994) and can be found at cell–matrix junctions in cultured cells (Lewis et al., 1996). The different subcellular pools of Abl may perform distinct functions, though Abl can translocate to nuclei in response to cytoplasmic cues (Lewis et al., 1996). Bcr-Abl exclusively localizes to the cytoplasm, suggesting that its role in oncogenesis involves cytoplasmic targets.

In Drosophila, Abl localizes to the axons of the central nervous system (CNS) (Bennett and Hoffmann, 1992). In epithelial cells, Abl’s localization varies with stage of development and tissue, but it is often concentrated near the apical cortex. Abl localizes to apical cell junctions soon after cells form and to the apical cytoplasm during gastrulation and in imaginal discs. In contrast, it is diffusely cytoplasmic in extended germ band embryos.

Genetic analyses in mice and flies have begun to shed light on Abl’s biological function. abl mutant mice are embryonic-viable but runted and exhibit defects in develop-
ment of the bones, immune system, and sperm. A null mutation and a COOH-terminal truncation removing the actin binding domains have similar phenotypes, suggesting that the interaction with actin is functionally important (for review see Van Etten, 1999). Analysis of Abl function in mice is complicated by the presence of the related kinase Arg; mice lacking both abl and arg die as embryos with defects in neuromuscular junctions that may reflect problems in actin organization (Koleske et al., 1998).

In Drosophila, analysis of the single Abl homologue primarily revealed roles in neural development. abl mutants are pupal lethal with defects in retinal development (Henkemeyer et al., 1987); they also have subtle CNS defects in which certain axons stop short of innervating their target muscles (Wills et al., 1999b). Much more severe CNS defects are seen in abl mutants that are also heterozygous or homozygous for the neural cell adhesion molecule fasciclin, the receptor tyrosine phosphatase dLAR, the axon guidance receptor robo, the adaptor disabled (dab), the Rho-family GEF trio, or the actin regulator profilin (for review see Lanier and Gertler, 2000). These data led to a model in which Abl transduces signals from neural cell surface receptors, influencing actin dynamics in growth cones.

In doing so, Abl is thought to act via one of its substrates, Enabled (Ena; Comer et al., 1998). Originally identified as a suppressor of abl; dab/+ mutants (Gertler et al., 1990), Ena is a member of the Ena/VASP family (for review see Lanier and Gertler, 2000), which modulate actin dynamics (Gertler et al., 1996). Drosophila ena mutants are embryonic lethal with defects in the CNS and its peripheral projections (Gertler et al., 1990; Wills et al., 1999a). The effects of ena mutations are opposite to those of abl; ena goes past their muscle targets rather than stopping short, consistent with the idea that Abl negatively regulates Ena. Like Abl, Ena is thought to act downstream of the axon guidance receptors Robo (Bashaw et al., 2000) and dLAR (Wills et al., 1999a), mediating cytoskeletal events.

Our interest in abl emerged from its genetic interactions with the adherens junction protein Armadillo (Arm; Loureiro and Peifer, 1998). We investigate morphogenesis, the process by which animals create their complex body plans by organizing cell shape changes and rearrangements. Epithelial cells must remain in intimate contact throughout morphogenesis, and in order to change shape or move must coordinate their actin cytoskeletons. Cells accomplish these tasks via cell–cell adherens junctions, which form a continuous adhesive belt around the apex of each cell that anchors a contractile ring of actin filaments (for review see Tepass et al., 2000). Junctions are organized around transmembrane cadherins. Human E-cadherin mediates cell–cell adhesion and organizes a multiprotein complex of catenins bound to its cytoplasmic tail, binding directly to β-catenin, which in turn anchors actin via interactions with α-catenin. Drosophila E-cadherin, Arm (the β-catenin homologue), and α-catenin function similarly.

Cadherin-catenin–mediated adhesion must be dynamic, allowing cell movement during morphogenesis (for review see Tepass et al., 2000). We used a genetic approach in Drosophila to identify regulators of epithelial morphogenesis. abl mutations substantially enhance the CNS defects of arm mutants. Further, abl genetically interacts with arm in the epidermis (Loureiro and Peifer, 1998). This suggested that Abl acts in epidermal cells during morphogenesis. Thus, we investigated whether Abl regulates epithelial development in Drosophila. Previous studies of Abl function relied on zygotic mutations, and thus the maternal contribution of Abl may have masked roles in other developmental processes. We removed this maternal contribution, analyzing abl maternal/zygotic mutants. This revealed a requirement for Abl in epithelial morphogenesis. Here we report the characterization of this role.

Results
Abelson is essential for embryonic morphogenesis

Previous studies identified a role for Abl in the CNS. Zygotic abl mutants have subtle CNS defects, that are enhanced in double mutant combinations (for review see Lanier and Gertler, 2000). We found previously that abl interacts with arm in its role as a catenin during CNS development (Loureiro and Peifer, 1998), where Arm works with N-cadherin (Iwai et al., 1997). We also observed genetic interactions between abl and arm in the epidermis. Thus, we hypothesized that Abl might also act in epithelial cells, and that this role might be masked by maternally contributed Abl. To test this, we removed maternal and zygotic Abl using the FLP dominant female sterile technique (Chou and Perrimon, 1996) to generate abl heterozygous females whose germ lines are homozygous abl mutant. These females contribute no wild-type Abl to their progeny. When crossed to

Figure 1. Complete loss of Abl disrupts CNS development. (A) Cell extracts from 3-h-old wild-type embryos or embryonic progeny of females with abl mutant germ lines, immunoblotted with anti-Abl antibody. Wild-type Abl is ~180 kD (top arrow). abl does not produce a protein recognized by this antibody. abl produces a truncated protein product of ~80 kD (bottom arrow). (B–F) Embryos (anterior up) labeled with mAb BP102, which labels all axons. (B) Wild-type CNS, with a scaffold of longitudinal (arrowhead) and commissural (arrow) axons. (C and D) Maternally abl mutant but zygotically-rescued embryos have relatively wild-type CNS development, with occasional collapsed longitudinal axons (D, arrowhead) and gaps in axon bundles (D, arrow). (E and F) abl mutants exhibit severe disruptions in CNS development. Most exhibit loss of commissural axons (arrow, E) and some have defects in both longitudinal and commissural axons (F). Bar, 25 μm.
The ventral nerve cord. Zygotic growth using the antibody BP102, which labels all axons of role was first defined in the CNS, we examined axon out-
to adulthood (Table I and unpublished data). Since Abl’s those that receive wild-type paternal Abl survive and go on
subtle defects in CNS development (Wills et al., 1999b).

We found that in

embryos (Gertler et al., 1989). In contrast, maternal/zygotic abl mutants have severe defects in CNS development
(Fig. 1, E and F). One common feature was a reduction in
the commissures which cross the midline. This phenotype
resembles that of abl dab double mutants (Gertler et al.,
1989) and is consistent with previous analysis of the effects
of Abl overexpression, which had the opposite effect:
enhanced midline crossing (Bashaw et al., 2000). Thus, mater-

al Abl obscures a role for Abl in CNS axon outgrowth.

We then examined whether Abl plays a role in epithelial
development that is obscured by maternally contributed Abl. We first looked at the cuticle, secreted by the epidermal
epithelium. ablMZ mutants exhibit defects in three morpho-
genetic processes, all of which require orchestrated cell shape
changes and cell migration: germ band retraction, head invo-
lution, and dorsal closure (Table II). Approximately 7% of
ablMZ mutants completely fail to germ band retract or com-
plete head involution (Fig. 2 B), whereas ∼14% exhibit par-
tial germ band retraction and dorsal closure defects (Fig. 2
C). Approximately 67% of ablMZ mutants have more subtle
defects in dorsal closure (Fig. 2, D and F), whereas ∼12%
are wild-type in appearance or have minor head involution
defects. In contrast, abl maternal mutants that inherit a pa-

ternal wild-type abl gene are rescued to normal embryogene-
sis and adulthood; most hatching larvae are wild-type
whereas 5% have slight defects in germ band retraction and
dorsal patterning. Previous work revealed that certain Abl
functions require kinase activity, whereas others do not
(Henkemeier et al., 1990). We found that maternal Abl’s
role in morphogenesis requires kinase activity, as both the
embryonic phenotype and adult viability are rescued by a ki-
nase-active Abl transgene but not by a kinase-dead version
(Table I; unpublished data).

One important clue to Abl’s function may come from its
intracellular localization. Previous work (Bennett and Hoff-
mann, 1992) documented that Drosophila Abl is found in ax-
on of the CNS. Abl is also expressed in epithelial cells, with
enrichment in the apical cortical cytoplasm during cellular-
ization, early gastrulation, and in the epithelial cells of the
imaginal discs. In later embryos, it is diffuse in the cytoplasm.
The original Abl antibody from the Hoffmann lab is no
longer available. We attempted to extend this work by gener-
ating an anti-Abl polyclonal antibody. This works well on

| Genotype              | Percentage hatched | n    |
|-----------------------|-------------------|------|
| abl1 glc x +/+        | 92.9              | 878  |
| abl1 glc x +/+        | 89               | 365  |
| abl2 glc x shg201/+    | 39.5             | 283  |
| abl2 glc x shg201/+    | 71.1             | 669  |
| abl2 glc x shg201/+    | 70.4             | 409  |
| abl2 glc x shg201/+    | 92.3             | 339  |
| abl2 glc x abl+/+      | 41.0             | 751  |
| abl2 glc x abl+/+      | 35.6             | 1149 |
| abl2 glc; TnAblWT + x abl+/+ | 76     | 290  |
| abl2 glc; TnAblK-N + x abl+/+ | 40     | 299  |
| abl2 glc; ena or +/+ x abl+/+ | 61     | 142  |
| abl2 glc; x shg201+; abl+/+ | 35.4         | 398  |
| abl2 glc x shg201+; abl+/+ | 38     | 522  |

abl heterozygous males, half the progeny are maternally and
zygotically abl mutant, while the other half receive a wild-
type copy of abl paternally. We used two abl alleles: abl produces a truncated protein, and abl is a protein null (Bennett
and Hoffmann, 1992; Fig. 1 A). The results were essentially identical with both alleles, and, where tested, were identical when embryos were transheterozygotes.

Embryos lacking both maternal and zygotic Abl (below referred to as ablMZ) die at the end of embryogenesis, while those that receive wild-type paternal Abl survive and go on
to adulthood (Table I and unpublished data). Since Abl’s role was first defined in the CNS, we examined axon out-
growth using the antibody BP102, which labels all axons of the ventral nerve cord. Zygotic abl mutant embryos have subtle defects in CNS development (Wills et al., 1999b).

We found that in abl maternal mutants that are paternally rescued (identified using a green fluorescent protein [GFP]-
marked chromosome), the CNS is normal or has subtle de-
fects (Fig. 1, C and D) which resemble those of abl dab/ abl+/ embryos (Gertler et al., 1989). In contrast, maternal/
immunoblots (Fig. 1 A), but does not show specific staining in situ, as assessed using embryos maternally and zygotically mutant for the protein-null ablΔ (unpublished data).

Loss of Abl disrupts cell migration and cell shape changes during dorsal closure

Previous studies supported a role for Abl in signaling from cell surface receptors to the actin cytoskeleton during axon outgrowth (Wills et al., 1999a; Bashaw et al., 2000). Having identified a role for Abl in epithelial tissues, we hypothesized that Abl might act there by a similar mechanism. One place to address this is during dorsal closure, when lateral epidermal epithelial sheets migrate toward the dorsal midline, enclosing the embryo in epidermis. Dorsal closure involves dynamic actin reorganization to form an acto-myosin purse string in cells at the leading edge of the sheet (Young et al., 1993), as well as orchestrated cell shape changes and cell migration (Kiehart et al., 2000). Since Abl plays a role in dorsal closure, we wondered whether Abl modulates these cellular events.

To compare cell shape changes and cell migration in wild-type and ablΔ mutants, we examined embryos during dorsal closure, using antiphosphotyrosine to label both adherens junctions and the leading edge actin cable. As wild-type dorsal closure initiates, leading edge cells elongate uniformly along the dorsal-ventral axis, perpendicular to the leading edge (Fig. 3 A, arrow). As closure proceeds, successive rows of cells lateral to the leading edge also uniformly elongate (Fig. 3, B and C, arrow). The lateral epithelial sheets eventually meet at the dorsal midline, and cells intercalate with one another, making the dorsal surface a continuous epithelial sheet with little midline discontinuity (Figs. 3, D and E, arrow).

ablΔ mutants have striking defects in the cellular events of dorsal closure. Cells fail to change shape in a coordinated fashion (Fig. 3, F–J). As leading edge cells begin to elongate, cells do not elongate uniformly in comparison to their neighbors (Fig. 3, F and G, arrows), and groups of cells have overly broad or narrowed leading edges (arrowheads). As cell shape is likely maintained against tension along the leading edge from the actin cable, altered cell shapes may result from alterations in the polymerization or anchoring of actin (see below). We also observed groups of cells that completely fail to change shape (Fig. 3, G–I, asterisks). As closure proceeds, the cell shape defects persist as cells behind the leading edge begin to elongate (Fig. 3, G–I). Not all ablΔ mutants close dorsally, but those that do show a variety of defects at the cellular level. Some embryos maintain groups of cells that have never elongated (Fig. 3 I, asterisks). Other embryos fail to properly align the opposing epithelial sheets at the midline upon completion of closure (Fig. 3 J, arrow), likely contributing to the altered dorsal hair patterning evident in the cuticles (Fig. 2 F). A subset of the ablΔ mutants fail to complete germ-band retraction (Figs. 2 C and 3, K and L). In these embryos, cells along the leading edge exhibit the same cell shape abnormalities during dorsal closure as mutants that complete germ-band retraction (Fig. 3 L, arrows). A fraction of the cells in ablΔ mutants become multinucleate due to defects in cellularization (unpublished data). We verified that cell shape and migration defects during dorsal closure are independent of cell shape disruption due to polyploidy (Fig. 3 O).

The failure to initiate uniform cell shape changes in ablΔ mutants is similar to the phenotype we observed in arm zygotic mutants (McEwen et al., 2000). These embryos have only maternal Arm, and thus their levels of wild-type Arm are substantially reduced. While arm mutants are more severely compromised in their ability to complete dorsal closure than are ablΔ mutants, leading edge cells of both arm (Fig. 3, M and N) and ablΔ mutants fail to elongate uniformly as closure is initiated.

The defects in cell morphology during dorsal closure in ablΔ mutants led us to examine localization of actin and of the Abl target Ena, an actin regulator during this process. In the initial stages of dorsal closure, as cells along the leading edge begin to elongate, Ena surrounds the cell membrane but is enriched at vertices of cell–cell contact and at adherens junctions of leading edge cells (Fig. 4 A, left, red). Actin localizes around the entire cell and begins to accumulate at the leading edge at this stage (Fig. 4 A, middle, green; Young et al., 1993). As closure proceeds, Ena accumulates at uniformly high levels in adherens junctions of leading edge cells (Fig. 4 C, left, red), while actin forms a uniform and tightly localized band along the leading edge (Fig. 4 D middle, green).

The localization of both Ena and actin is altered during dorsal closure in ablΔ mutants, and these changes parallel the changes in cell shape. As closure initiates, Ena is enriched at adherens junctions, but the level of Ena is not
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uniform in different cells (Fig. 4 B, arrow vs. bracket). The actin cable is also not uniform; levels of actin often change in parallel to Ena (Fig. 4 B). This uneven distribution of Ena and actin correlates with defects in cell shape. Cells with constricted leading edges tend to accumulate abnormally high levels of both proteins, whereas cells with broadened leading edges tend to have lower levels of Ena in junctions and lower levels of leading edge actin. This correlation may be explained by the fact that the leading edge is under tension, presumably due to the contractile actin cable (Kiehart et al., 2000). Defects in actin cable assembly or anchoring within individual cells could lead those cells to splay open at the leading edge; adjacent cells might then hypercontract due to the release of the tension normally exerted by their neighbors.

Figure 4. Complete loss of Abl alters Ena and actin localization during dorsal closure. Lateral view. Embryos double-labeled with anti-Ena (red) and phalloidin (green), labeling F-actin. (A) Stage 13 wild-type embryo with leading edge cells initiating elongation. Ena (left, red) is enriched at vertices of cell–cell contact. Actin (middle, green) outlines all cell membranes and is beginning to accumulate at the leading edge. Actin and Ena colocalize at cell junctions. (B) Stage 13 ablMZ mutant. Ena (left, red) and Actin (middle, green) enrichment is not uniform at the leading edge. Both are enriched in some cells (arrows) and depleted in others (brackets). (C) Stage 14 wild-type embryo. More lateral cells have undergone uniform elongation. Ena is uniformly enriched at adherens junctions of leading edge cells (left, red). Actin forms a tight cable along the leading edge (middle, green). Ena and actin colocalize at adherens junctions as actin expands along the entire leading edge. (D) Stage 14 ablMZ mutant. Nonuniform localization of Ena and Actin persists. Cells with excess Ena (left, arrow) often accumulate excess Actin (middle, arrow), whereas cells with diminished Ena levels (left, bracket) have diminished levels of Actin (middle, bracket). Bars, 10 μm.
Dorsal closure is slowed in abl mutants

Multiple forces drive dorsal closure, including forces generated by cell shape changes, contraction of the leading edge actin-myosin cable, and pulling forces exerted by amnioserosa cells. These forces act combinatorially, so disruption of one force slows but does not prevent closure (Kiehart et al., 2000). ablMZ mutants display defects in both cell shape and in the actin cable, yet many embryos complete closure, albeit imperfectly. To analyze how ablMZ mutants compensate for disruptions in cell shape and the actin cable, we performed time-lapse confocal microscopy on embryos undergoing closure (see videos available at http://www.jcb.org/cgi/content/full/jcb.200105102/DC1). We analyzed transgenic flies expressing the actin binding domain of Moesin fused to GFP (Kiehart et al., 2000), allowing us to visualize actin dynamics in real time.

During dorsal closure in living wild-type embryos, the leading edge becomes uniformly enriched in actin. Amnioserosa cells, the large squamous cells exposed on the dorsal surface of the embryo, undergo apical constriction (Kiehart et al., 2000), decreasing in surface area throughout closure (Fig. 5 A). Amnioserosa cells are undergoing apical constriction and the embryo is zipping together at the anterior and posterior ends (arrows). During dorsal closure in living wild-type embryos, the leading edge becomes uniformly enriched in actin. Lateral epithelial sheets elongate uniformly. (D) 30 min. Amnioserosa cells are undergoing apical constriction and the embryo is zipping together at the anterior and posterior ends (arrows). (C) 60 min. Amnioserosa cells have constricted apically and remain in the same plane of focus as the lateral epithelial sheets. (D) 90 min. Dorsal closure is complete. (E–K) ablMZ mutant. The amnioserosa cells in E are comparable in surface area to the wild-type in A. (F–H) As closure progresses, amnioserosa cells constrict and lateral epithelial cells elongate, but dorsal closure is delayed relative to wild-type (compare D and H). If one matches embryos based on the length of the leading edge (compare A and G), closure is still delayed. This embryo took >4 h to complete closure (K). (L–R) A different ablMZ mutant at higher magnification, illustrating the folding-under of the leading edge and failure to complete closure. (S) Cross-section diagram depicting one interpretation of the defects of ablMZ mutants. In wild-type embryos, the rate at which lateral cells elongate, the sheets migrate, and amnioserosa cells constrict are tightly coordinated. In ablMZ mutants, the leading edge folds under the more lateral epidermis, perhaps because leading edge cells migrate too slowly or amnioserosa cell constriction is slowed (these events are likely coupled), forcing the sheet to fold under. Time-lapse videos supplementing this figure are available at http://www.jcb.org/cgi/content/full/jcb.200105102/DC1. Bars, 25 μm.
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initiate elongation and the front is enriched in actin, dorsal closure is completed in a little over 1.5 h.

Dorsal closure is substantially slowed in ablMZ mutants. It is not simple to define an equivalent starting point for ablMZ and wild-type embryos, as the dorsal/ventral extent of the amnioserosa is larger in ablMZ mutants, both in cell number and distance (compare Fig. 5 A to E). This may be due to defects in cell rearrangements during germband retraction. However, regardless of whether we compared embryos with equivalent amnioserosa surface areas (Fig. 5 A vs. E) or with roughly equivalent length leading edges (Fig. 5 A vs. G), closure is substantially delayed in ablMZ mutants, taking two to three times longer than normal. At the cellular level, lateral cells elongate on schedule in the mutants (despite defects in cell shape) and amnioserosa cells apically constrict, though more slowly than in wild-type.

Time-lapse imaging also revealed defects that were not apparent in our fixed images. As closure proceeds, the leading edge of the lateral epidermis folds under the more lateral cells that follow it (Fig. 5, J, Q, and R). This suggests that while lateral epithelial cells continue to elongate and migrate, driving sheet extension, leading edge cells do not migrate toward one another at an appropriate rate (diagram in Fig. 5 S). Our movies also suggest that filopodial extensions from the leading edge might aid in the eventual closure, as they do in wild-type (Jacinto et al., 2000), actively zipping the epidermal sheets together. Filopodial extensions from epidermal and amnioserosa cells are present in both wild-type and ablMZ mutants, and even appear more fre-

Figure 6. Ena and Arm colocalize at adherens junctions throughout development. All images (except I) are anterior to the right. Ena is green and Arm is red in merged images. (A) Stage 3 egg chamber. Ena and Arm are enriched in apical adherens junctions of follicle cells. (B and C) Stage 10 egg chamber. Levels of Ena and Arm drop, but both remain at adherens junctions. Anterior (border cells) and posterior polar follicle cells are enriched in both Ena and Arm (B, arrows). Ena and Arm also colocalize to nurse cell membranes (B, arrowhead). (D–G) During embryogenesis Ena and Arm colocalize to adherens junctions of epithelial tissues. (D) Cross-section, stage 9 embryo. Ectodermal adherens junctions (arrow). (E) Adherens junctions of polarized cells of the invaginating hindgut (arrow). (F) Apical view, stage 9 embryo. Ena is enriched at vertices of cell–cell contact (arrow), whereas Arm is more uniform. (G) During dorsal closure Ena is enriched at adherens junctions of leading edge cells, but it is also found in the cytoplasm of cells at the segment boundary (arrowheads). (H) Ena and Arm both localize to axons. (I–K) Imaginal discs. (I) Apical surfaces of two epithelial sheets opposed to one another in the wing imaginal disc (arrow). Ena and Arm colocalize to apical adherens junctions, and are also found at the apical surface. (J and K) In eye imaginal discs cell differentiation occurs after the morphogenetic furrow passes. In undifferentiated cells, Ena and Arm colocalize to cell boundaries (J, arrowhead). As groups of cells begin differentiating as photoreceptors (J, arrow), Ena localizes uniformly to all cells of the precluster. Arm, in contrast, accumulates at high levels in a subset of these cells. Later, Ena and Arm colocalize in photoreceptor rhabdomeres (K, arrow). Bars: (A–J) 10 μm; (K) 50 μm.
quent in late-stage mutants (Fig. 5, B, H, and N, insets). We suspect epithelial sheet migration is compromised in abl mutants due to the discontinuity of the leading edge actin cable and the cell shape defects. In this situation, filopodia may be needed to locate the opposing epidermis and eventually zip up the embryo.

**ena suppresses the abl phenotype and localizes to adherens junctions**

The best characterized substrate of Drosophila Abl is Ena. Mutations in ena suppress the effects of abl dab mutations (Gertler et al., 1995). We thus examined whether ena might act with Abl in epithelial morphogenesis. Data from the Hoffmann lab supported this possibility: they found that females homozygous for abl mutations, which are normally sterile, become fertile when they are also heterozygous for ena (Bennett and Hoffmann, 1992). We thus generated homozygous abl germline clones in females that were heterozygous for ena (Gertler et al., 1995). We thus generated homozygous abl germline clones in females that were heterozygous for ena (for experimental reasons only 50% of the females generated in the experiment are ena heterozygotes) and crossed them to abl heterozygous males. ena heterozygosity significantly rescued the ablZ embryonic lethality (Table I).

These data suggest that Ena misregulation contributes to the defects in morphogenesis we observed in ablZ mutants. We thus examined Ena localization in epithelial tissues, as this might reveal, at least in part, where Abl is acting. We used two different anti-Ena antibodies (Gertler et al., 1995; Bashaw et al., 2000) with similar results. We found that Ena colocalizes with Arm at adherens junctions throughout most stages of development. During early oogenesis, Ena and Arm are strongly enriched at adherens junctions of follicle cells surrounding the germline (Fig. 6 A; Baum and Perrimon, 2001) and remain enriched at junctions, though at lower levels as oogenesis proceeds (Figs. 6, B and C). During embryogenesis, Ena begins to accumulate in adherens junctions at the onset of gastrulation (unpublished data) and colocalizes with Arm at adherens junctions in germband-extended embryos (Fig. 6 D, arrow) and in fully polarized cells, such as the invaginating hindgut (Fig. 6 E, arrow). Arm localizes uniformly around cells (Fig. 6 F), whereas Ena, though present all around the plasma membrane, is enriched at vertices of cell–cell contact (Fig. 6 F, arrow). Ena is strongly enriched in adherens junctions of leading edge cells during dorsal closure (Figs. 4 C and 6 G), and also localizes to the cytoplasm in a stripe of epidermal cells at the segmental boundary (Fig. 6 G, arrowheads). Ena and Arm also localize to CNS axons (Gertler et al., 1990; Fig. 6 H). During larval development, Ena and Arm are strongly enriched at adherens junctions of the highly polarized imaginal disc epithelia, precursors of the adult epidermis (Figs. 6 I, arrow), as well as in the specialized junctions of the photoreceptor rhabdomeres (Fig. 6 G, arrow heads). Thus, Arm and Ena colocalize in adherens junctions in most epithelial cells.

**ena and arm genetically interact during dorsal closure**

Our genetic experiments suggest that Ena misregulation plays a role in the defects in morphogenesis of ablZ mutants (Table I). As Ena localizes to adherens junctions, we wondered whether it might work with adherens junction components during morphogenesis. We thus looked for genetic interactions between ena and arm. We crossed females heterozygous for mutations in both arm and ena to males heterozygous for ena. Both arm and ena are embryonic lethal; as armZ is on the X-chromosome, we expect 43% of the dead progeny to be arm mutant, 43% to be ena mutant, and 14% to be armZ; ena double mutants. Null alleles of Arm have dorsal closure defects, due to a combination of affects on cell adhesion and Wg signaling (McEwen et al., 2000), whereas weaker arm alleles do not have dorsal closure defects. We first tested the weakest allele of arm, armH8.6, in which dorsal closure is normal, although segment polarity is affected (Fig. 7 B). Although ena homozygotes are embryonic lethal, most of the dead embryos only have mild defects in head involution (Gertler et al., 1990; Fig. 7 C). A small fraction (~5%) have dorsal pattern defects indicative of mild problems in dorsal closure. When we generated armH8.6; enaZC1 double mutants, we found strong synergistic defects in both head involution and dorsal closure (Fig. 7 D; Table III). Mutations in ena also enhance the dorsal closure defects of the stronger arm mutants armZ1M0, armH8.6 (unpublished data), and armYD35 (Fig. 7, E and F; Table III), though it is difficult to rule out the possibility that these interactions are simply additive.

![Figure 7. Mutations in ena enhance arm’s dorsal closure defects.](Image)
Mutations in DE-cadherin enhance the abl phenotype

The genetic interactions between arm and abl in the CNS and epidermis (Loureiro and Peifer, 1998) and the localization of Ena to adherens junctions suggest that Abl might act in part at adherens junctions. In cultured mammalian cells Abl localizes to cell–matrix junctions (Lewis et al., 1996). As one test of the possible sites of Abl action during morphogenesis, we looked for dose-sensitive genetic interactions between abl and genes encoding proteins involved in epithelial adhesion: DE-cadherin (encoded by shogun (shg); Tepass et al., 1996; Uemura et al., 1996), which mediates cell–cell adhesion, and scant (scb), an integrin α-chain which mediates cell-matrix adhesion during dorsal closure (Stark et al., 1997).

We saw strong genetic interactions of abl with the cadherin shg, but not with the integrin scb. We crossed females with abl mutant germelines to males heterozygous for shg or scb. All progeny lack maternal Abl and are zygotically abl heterozygous, receiving a wild-type copy paternally. Zygotic null allele, /H9251 , arm 4 /H11001 , and genes encoding proteins involved in epithelial skeleton. We thus examined the subcellular localization of adherens junction proteins and other markers of cell polarity in MZ mutants. To control for variability between experiments, we analyzed mixed populations of wild-type and mutant embryos that had undergone simultaneous fixation, staining, and microscopy. We used a wild-type strain carrying a GFP transgene, allowing us to unambiguously discriminate between wild-type and mutant embryos. The mutant embryos had fathers which were heterozygous for abl and a different GFP-transgene, to differentiate ablMZ from paternally rescued embryos.

Figure 8. DE-cadherin (shg) genetically interacts with Abl. Cuticle preparations, anterior up. (A) Wild-type. (B) ablM/ablM × shgCyO. ablM maternal mutants are zygotically rescued, with all hatching as larvae and most appearing wild-type. shg heterozygosity prevents zygotic rescue of abl maternal mutants and leads to morphogenesis defects. Note defects in dorsal closure and head involution (arrow). (C) ablMZ mutants die during embryogenesis with defects in epithelial morphogenesis. (D and E) shg heterozygosity enhances the ablMZ phenotype. (D) 70% of lethal progeny of ablM/ablM × shg+/shg+; ablMZ/+/ have cuticles that are reduced in size with a large dorsal-anterior hole. (E) 30% of the lethal progeny of ablM/ablM × shg+/shg+; ablMZ/+/ have a prominent dorsal-anterior hole.

Loss of Abl decreases the amount of junctional arm and α-catenin

The genetic interactions between abl and shg suggested that some of the morphogenesis defects observed could result from effects of Abl at adherens junctions. Alternately, they might result from more nonspecific effects on cell polarity or the cytoskeleton. We thus examined the subcellular localization of adherens junction proteins and other markers of cell polarity in ablMZ mutants. To control for variability between experiments, we analyzed mixed populations of wild-type and mutant embryos that had undergone simultaneous fixation, staining, and microscopy. We used a wild-type strain carrying a GFP transgene, allowing us to unambiguously discriminate between wild-type and mutant embryos. The mutant embryos had fathers which were heterozygous for abl and a different GFP-transgene, to differentiate ablMZ from paternally rescued embryos.

Table III. arm and ena genetically interact

| Cross | arm α-type | ena α-type | arm; ena | n  |
|-------|------------|------------|----------|----|
| arm4/H4;+; ena4/H4+ × +/Y; ena4/H4+ | 34 | 53 | 13 | 218 |
| arm4/H4;+; ena4/H4+ × +/Y; ena4/H4+ | 51 | 35 | 14 | 635 |
| Predicted by Mendelian ratios | 43 | 43 | 14 |  |

Percentage of dead embryos with:

- abl+/+; shg+/ or ablMZ/+/; scbMZ+ males. Half of the progeny lack both maternal and zygotic Abl, and half of those are also heterozygous for either shg or scb. Heterozygosity for shg substantially enhanced the ablMZ phenotype (Fig. 8 D; Table II). Approximately half of the dead embryos (presumably those that were ablMZ/+, shg+/+ had a prominent dorsal anterior hole not seen in ablMZ mutants (Fig. 8 D); these embryos also had the typical spectrum of dorsal closure and germ band retraction defects. We saw similar phenotypic enhancement in ablMZ embryos heterozygous for the shg null allele, shgpos (Fig. 8 E; Table II). In contrast, this sensitized assay did not uncover a significant genetic interaction between abl and scb (Table II).
ablMZ mutants had reduced levels of Arm in adherens junctions. This was first noticeable in germband-extended embryos (Fig. 9, A and B) and became more pronounced during dorsal closure in wild-type (Fig. 9, C and D). Cross-sectional views suggest that the decrease in Arm at adherens junctions is not due to mislocalization of Arm to a different place in the cell (unpublished data), and we also think it is unlikely to be solely due to the alterations in cell shape in the mutant. Given these effects on Arm, we analyzed other adherens junction components. α-catenin, a protein that links Arm to the actin cytoskeleton, also showed reduced accumulation in adherens junctions (Fig. 9, E and F). The localization of both Arm and α-catenin was more variable in paternally rescued embryos, with reduction in some individuals but not others (unpublished data). The accumulation of DE-cadherin at junctions also may be slightly reduced in ablMZ mutants (Figs. 9, G and H), but this effect was less pronounced than that on Arm or α-catenin. We also examined several other cortical or membrane markers. The accumulation of phosphotyrosine in adherens junctions (Fig. 9, I and J), Coracle at septate junctions (Fig. 9, O and P), Neurotactin at the basolateral membrane (Fig. 9, K and L), and Crumbs at the apical membrane (Fig. 9, M and N) were only slightly reduced or unaffected. In doing these experiments, we also observed that the defects in cell shape in ablMZ mutants are not restricted to dorsal closure. We observed defects in the uniform apical constrictions that occur in cells along the ventral midline (Fig. 9, A and B). Defects in cell shape changes and cell migration could also explain the observed defects in germband retraction.

To complement these immunofluorescence assays, we examined total protein levels of Arm and other proteins in the progeny of ablMZ germline mutant females crossed to abl heterozygous males. Half of these embryos are ablMZ and the other half are zygotically rescued. To ensure that embryos were similarly aged and to remove unfertilized eggs from the samples, we selected living embryos at the cellular blastoderm stage and then let them develop for given amounts of time. Total levels of Arm protein are significantly reduced throughout development compared with wild-type (Fig. 10, A–C). Similar reductions in Arm protein were observed in abl1 (unpublished data). In contrast to Arm, the levels of two unrelated control proteins, Pnut and BicD, were unaffected by loss of Abl function (Fig. 10, A–C). We next examined the levels of other adherens junction proteins. Reduction in Abl function also led to reduction in α-catenin protein levels (Fig. 10 A). In contrast, levels of DE-cadherin are not altered in abl mutants (Fig. 10, A–C). We then assessed whether these effects were specific for adherens junction proteins, by examining the levels of other markers of cell polarity or the cytoskeleton. We saw either subtle reduction or no effect of abl mutations on the levels of actin, the septate junction protein Coracle, and the apical marker Crumbs (Fig. 10, B and C).
Abl is thought to antagonize Ena in this process. The *ena* and *abl* phenotypes were surprising in one respect. Ena/VASP proteins had been thought to enhance actin polymerization at the adherens junctions. However, while promoting actin polymerization might be expected to drive growth cone extension and axon outgrowth, Ena promotes growth cone repulsion and axon stalling (Bashaw et al., 2000; Wills et al., 1999a,b), whereas Abl has opposite effects. Work in cultured fibroblasts led to similar conclusions: Ena/VASP proteins inhibit cell migration (Bear et al., 2000).

Building on this model, Abl and Ena might play analogous roles in epithelial cells, translating extracellular signals into changes in the actin cytoskeleton. This sort of cytoskeletal modulation plays a key role in cell migration and cell shape changes during epithelial morphogenesis. One model consistent with our data is that Abl acts at adherens junctions during morphogenesis. Cadherins and catenins play important roles in morphogenesis in all animals. Severe reduction in *Drosophila* Arm (Cox et al., 1996) or DE-cadherin (Tepass et al., 1996) function leads to early loss of epithelial integrity. Less severe reduction in cadherin/catenin function affects head involution, dorsal closure, and other morphogenetic processes (Tepass et al., 1996; Uemura et al., 1996; McEwen et al., 2000). In fact, many epithelial defects of *DE-cadherin* mutants are blocked by blocking morphogenetic movements (Tepass et al., 1996), suggesting that modulating adhesion is critical to morphogenesis.

Several lines of evidence support the possibility that the morphogenetic defects of *abl* mutants result, at least in part, from Abl action at adherens junctions. First, the effects on dorsal closure, germband retraction, and head involution are strongly enhanced by reducing the dose of DE-cadherin. Second, the defects in cell shape during dorsal closure resemble, in part, those of *arm* mutants. Third, the defects in morphogenesis are suppressed by mutations in *ena*, which is primarily found at adherens junctions. Finally, we observed a reduction in junctional Arm and α-catenin in *abl* mutants. It is important to note, however, that any role for Abl at adherens junctions would be a modulatory one. It is not absolutely essential for adherens junction assembly or function. Of course, it remains possible that other tyrosine kinases may act redundantly with Abl. The relationship between the cadherin-catenin system, Abl, and Ena that may occur in epithelial cells could also exist in the CNS. Arm and ΔN-cadherin play roles in axon outgrowth in *Drosophila*, and in this role *arm* interacts genetically with *abl* (Iwai et al., 1997; Loureiro and Peifer, 1998).

One target of Abl might be Ena, which could regulate actin dynamics in the actin belt underlying the adherens junction. Just as local modulation of actin dynamics likely regulates growth cone extension or stalling, the cell shape changes and cell migration characteristic of morphogenesis will require modulation of actin dynamics and junctional linkage. The idea that Ena may regulate cell–cell adhesion recently received strong support from work in cultured mammalian keratinocytes, where inhibiting Ena/VASP function prevented actin rearrangement upon cell–cell adhesion (Vasioukhin et al., 2000). This model was further supported by work published while our paper was under review, which demonstrated that both Ab1 and Ena regulate actin polymerization at the adherens junctions of ovarian follicle cells in *Drosophila* (Baum and Perrimon, 2001).

Other models are also consistent with our data. Abl may act directly on the actin cytoskeleton, with its effects on
junctions a more indirect consequence. Junctional linkage to actin is critical for effective cell adhesion (Hirano et al., 1992) and alterations in actin polymerization could affect the ability to assemble stable cadherin–catenin complexes, as was observed in cultured mammalian cells (Quinlan and Hyatt, 1999), resulting in the observed loss of Arm from junctions. Abl could also play a more general role in the establishment and maintenance of cell polarity. Finally, studies of cultured mammalian cells also suggest that Abl acts at cell-matrix junctions to modulate responses to integrin-focal adhesion proteins like paxillin and Crkl (for review see Van Etten, 1999). In doing so, it may influence both tethering to actin and signal transduction. Drosophila integrins play important roles in morphogenetic processes such as dorsal closure and germ band retraction (for review see Brown et al., 2000). We did not detect genetic interactions between abl and scab, the integrin α-chain that plays a role in dorsal closure (Stark et al., 1997). However, this does not rule out interplay between integrins and Abl in morphogenesis. It is now important to test these different models by investigating the mechanism by which Abl and Ena act during morphogenesis.

Materials and methods

Fly stocks and phenotypic analysis

All mutations are described in Flybase (http://flybase.bio.indiana.edu/). abl and abl<sup>+</sup> germ line clones were generated by the FLP dominant female sterile technique (Chou and Perrimon, 1996). 48–72-h-old hs<sup>lslp</sup>abf FRT 79D-F-EnvA<sup>D1</sup> FRT 79D-F-Lar larvae were heat shocked for 3 h at 37°C. Only homozygous abl mutant germ cells develop in these females. Stocks to generate abl germ line clones, hs<sup>lslp</sup>abf(D<sup>ENV</sup>A<sup>D1</sup>); FRT3L9D-F-EN<sup>V</sup>TM3, and ov<sup>10</sup> FRT3L9D-F-ENTM3, were from the Bloomington Drosophila Stock Center. abl and ena alleles were from M. Hoffmann (University of Wisconsin-Madison, WI). The wild-type was Canton-S. Transgenic lines express–anti–catenin, anticadherin (both 1:500), and anticrumbs (1:50).

Immunolocalization and immunoblotting

Embryos were bleach dechorionated and fixed for 20 min in 1:1:4 formaldehyde/0.1 M Pipes/2 mM MgSO<sub>4</sub>/1 mM EGTA/0.1% NP-40. Methanol. For DE-cadherin localization, embryos were fixed for 1 h in the same fix with 0.3% Triton X-100 added. Vitelline membranes were removed with methanol. For actin visualization, embryos were fixed for 5 min in 1:1:37 formaldehyde/80% methanol and their vitelline membranes were removed manually. Larval tissues were dissected in insect media and fixed in 4% paraformaldehyde in PBS for 20 min. Ovaries were dissected and fixed as in Peifer et al. (1993). All tissues were blocked and stained in PBS/1% goat serum/0.1% TritonX-100 (PBS/2% BSA/0.3% Triton X-100 was used for DE-cadherin staining). Antibodies used were mouse monoclonals anti-tublin (Upstate Biotechnology; 1:1000), anti-Arm (1:500; Gertler et al., 1995), and rat monoclonals anti–α-catenin (1:250) (Oda et al., 1993) and anti–DE-cadherin (1:250) (Oda et al., 1994). Actin was visualized using Alexa 488 phallidin (Molecular Probes). For DNA visualization, embryos were treated with 300 μg/ml RNase for 30 min at room temperature and stained for 20 min with 10 μg/ml propidium iodide. A ZEISS 410 laser scanning confocal microscope was used. For biochemical experiments, embryos were placed in halocarbon oil to allow staging under the dissecting microscope, picked at the cellular blastoderm stage, and aged defined periods of time. Extract preparation and cell fractionation were as in Peifer et al. (1993). Samples were analyzed by 6% SDS-PAGE, transferred to nitrocellulose and immunoblotted with mouse anti-Arm N27A1 (1:500), anti-Bicaudal D (R. Suter, McGill University, Montreal, Canada; 1:500), anti-pnut at (DSHB; 1:30), antiactin (Chemicon; 1:250), rat anti–DE-cadherin1 (1:100), anti–α-catenin, anticolc (both 1:500), and anticrulb (1:50).

Time lapse microscopy

Wild-type embryos imaged were homozygous for Moesin-GFP (Kiehart et al., 2000), whereas abl<sup>+</sup> mutant embryos imaged were derived from abl<sup>+</sup> germ line clone females crossed to abl<sup>+</sup>, FRT 79D-F, moesin-GFP/TM3 males; thus, the only GFP fluorescent embryos in this collection are those that are abl mutant/zigotic mutants. Embryos were bleach dechorionated and mounted in halocarbon oil (series 700; Halocarbon Products Corporation) between a coverslip and a gas permeable membrane (Petriperm; Sar-torius Corporation). Images were captured every 30 s using a PerkinElmer Wallac Ultraview Confocal Imaging System, and image analysis was performed using NIH Image 1.62.

Online supplemental material

Time-lapse videos are available to supplement Fig. 5. Images were captured every 2 s and the videos are played at a rate of 10 frames/s. Videos are available at http://www.jcb.org/cgi/content/full/jcb.200105102/DC1.

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