Allocation of the thoracic imaginal primordia in the Drosophila embryo

Barbara Cohen 1, Amanda A. Simcox 3 and Stephen M. Cohen 1,2,*

1Department of Cell Biology, 2Howard Hughes Medical Institute, Baylor College of Medicine, Houston, TX 77030, USA
3Department of Molecular Genetics, Ohio State University, Columbus, Ohio 43210, USA

*Author for correspondence

SUMMARY

The primordia of the thoracic imaginal discs of the Drosophila embryo originate as groups of cells spanning the parasegment boundary. We present evidence that the thoracic imaginal primordia are allocated in response to signals from the wingless (wg) and decapentaplegic (dpp) gene products. Rows of cells that express wg intersect rows of cells that express dpp to form a ladder-like pattern in the ectoderm of the germ band extended embryo. The imaginal primordia originate as groups of cells which lie near these intersection points. We have used a molecular probe derived from the Distal-less (Dll) gene to show that this population contains progenitor cells for both the dorsal (i.e. wing) and ventral (i.e. leg) discs. Although we show that Dll function is not required for allocation of imaginal cells, activation of an early Dll enhancer may serve as a molecular marker for allocation. A group of cells, which includes the imaginal progenitors, activate this enhancer in response to intercellular signals from wg and perhaps from dpp. We have used a conditional allele of wg to show that wg function is transiently required for both allocation of the imaginal primordia and for initiation of Dll expression in these cells during the brief interval when wg and dpp form the ladder-like pattern. Allocation of the imaginal primordium and activation of Dll expression appear to be parallel responses to a single set of positional cues.

Key words: Distal-less, wingless, decapentaplegic, TGF-β, imaginal disc, pattern formation, limb development, Drosophila

INTRODUCTION

The epidermal structures of the adult head, thorax and terminalia of Drosophila derive from specialized precursors known as imaginal discs, which originate as clusters of cells in the embryonic ectoderm. Genetic analyses have shown that the disc primordia are first specified as groups of cells (Garcia-Bellido and Merriam, 1969; Garcia-Bellido et al., 1973; Garcia-Bellido et al., 1976; Wieschaus and Gehring, 1976a,b), known as polycyones (Crick and Lawrence, 1975). Somatic mosaic clonal analyses have shown that the imaginal primordia are subdivided into distinct anterior and posterior founder populations. The distinction between anterior and posterior polycyones exists from as early as genetically marked clones can be produced by mitotic recombination (i.e. one cell division after blastoderm; Wieschaus and Gehring, 1976b; Steiner, 1976; Lawrence and Morata, 1977). The boundary between anterior and posterior compartments is thought to correspond to the parasegment boundary in the embryo. The spatial relationship between the parasegment boundary and the imaginal primordia suggested that the discs are specified in response to positional signals from the wingless (wg) gene (Simcox et al., 1989; Cohen, 1990). wg encodes a member of the Wnt family of intercellular signaling molecules (Rijsewijk et al., 1987). The Wingless protein is secreted and can be detected over a range of 2-3 cells flanking the cells that express wg transcript (van den Heuvel et al., 1989; González et al., 1991). Thus the imaginal disc progenitor cells may be allocated in response to an intercellular positional signal transmitted by the secreted Wingless protein.

Morphological studies have documented the locations of the thoracic imaginal discs in the mature Drosophila embryo (Auerbach, 1936; Madhavan and Schneiderman, 1977; Bate and Martinez-Arias, 1991). By 10 hours of development the dorsal (wing and haltere) and ventral (leg) disc primordia form clearly recognizable, separate, groups of cells. The presumptive disc cells can be identified on the basis of their shape and histochemical staining properties (Bate and Martinez-Arias, 1991), as well as by expression of a number of genes including Distal-less (Dll), vestigial, and escargot (Cohen, 1990; Cohen et al., 1991; Williams et al., 1991; Whiteley et al., 1992; Hartenstein and Jan, 1992). Although the dorsal and ventral disc primordia are well separated when they are first recognizable, analysis of gynandromorphs and somatic mosaics induced by mitotic recombination has suggested that the leg and wing originate in very close proximity in the embryonic ectoderm. Clones of genetically marked cells induced at blastoderm stage were able to contribute to the formation of both the leg and wing discs (Wieschaus and Gehring, 1976b; Steiner, 1976; Lawrence and Morata, 1977). The distance between the centers of the leg and wing primordia was estimated to
be approximately equal to the diameters of the individual primordia (Wieschaus and Gehring, 1976a). These observations suggested that the dorsal and ventral disc primordia are likely to be immediately adjacent or possibly overlapping in the blastoderm stage embryo.

In this report we use molecular markers to trace the origins of the thoracic disc primordia in the early embryo. Dll expression labels the nascent leg primordium at approx. 5-5.5 hours of embryogenesis in clusters of cells located near the intersection between rows of cells that express wg and those that express decapentaplegic. We show that wg function is required at this time to initiate Dll expression and also for allocation of the thoracic imaginal disc primordia. We have used a molecular lineage tag derived from the Dll gene to follow the developmental fate of cells that originate in the ventral thoracic cluster. We observe that some of these cells are displaced dorsally to form the prothoracic, wing and haltere imaginal discs, while cells that remain in the original ventral position form the leg discs. These observations provide molecular evidence to support the proposal that wing and leg imaginal discs may arise from a common primordium in the early embryo.

MATERIALS AND METHODS

Histochemical methods

Affinity purified antibody to vestigial (Vg) protein was kindly provided by Jim Williams and Sean Carroll. The isolation of the Dll-lacZ reporter genes, production of antibody to DLL protein and antibody staining protocols are described in Vachon et al. (1992). The Dll-304 transgene consists of an early-acting Dll enhancer directing expression of lacZ. The Dll-215 transgene consists of a late-acting Dll enhancer directing expression of lacZ. Double labellings to visualize β-gal activity followed by RNA in situ hybridization or by antibody staining were done as described previously (Cohen et al., 1991; Vachon et al., 1992). Most fluorescent double labels were photographed by conventional microscopy. The double-labelled image of anti-β-gal and anti-Vg expression in the wing disc (Fig. 7) was taken on a confocal microscope.

Embryo culture

Dll mutant embryos were recovered from a cross of two different mutant alleles, Dll\textsuperscript{SA1} and Dll\textsuperscript{MP}, which lack all Dll function. MP is a large deletion removing the entire Dll transcription unit. SA1 is a 5.5 kb deletion which removes the exon encoding the aminoterminal 2/3 of the homeodomain. SA1 only affects the Dll transcription unit (Cohen et al., 1989; Cohen and Jürgens, 1989). The stocks were marked with yellow and balanced with a CyO chromosome carrying a yellow\textsuperscript{+} duplication (eg: y; Dll\textsuperscript{SA1}/CyO, bw Df(2R)B80 Dp(1;2) y\textsuperscript{+}). Mutant embryos produced by crossing the two strains are phenotypically identifiable by their yellow cuticle. Embryo culture was carried out as described by Simcox et al. (1989). The characteristic markers for the different leg regions are discussed in Table 1 and described in detail by Schubiger (1968).

Strains

The wg temperature-sensitive allele IL114 was used for temperature shift experiments (Nüsslein-Volhard et al., 1984). An enhancer detector insertion in the wg gene was used in studies to histochemically visualize wg-expressing cells (Perrimon et al., 1991). Isolation of the early and late-acting Dll enhancer-lacZ fusion strains is described in Vachon et al. (1992). The early-acting enhancer is called Dll-304. The late-acting enhancer is called Dll-215.

RESULTS

Molecular markers for the imaginal primordia

To visualize the development of the imaginal primordia throughout embryogenesis we made use of molecular markers from the Distal-less (Dll) and vestigial genes (Cohen, 1990; Williams et al., 1991). We will first describe the expression of these markers late in embryogenesis when the disc primordia are morphologically recognizable. Double-labelling experiments used a late-acting Dll enhancer element to direct expression of β-galactosidase (β-gal) protein in the leg disc primordia and antibody to Vestigial protein (Vg) to label the wing and haltere discs (Fig. 1). The wing and haltere discs invaginate as simple epithelial sacs, which can be visualized as clusters of cells that express Vg protein, in the late embryo (grey, Fig. 1A). The location of the leg disc clusters can be visualized by expression of β-gal protein under control of the Dll late enhancer (brown, Fig. 1A). The leg discs also invaginate, but remain closely apposed to the larval ectoderm (Bate and Martinez-Arias, 1991). In addition to the dorsal discs, Vg is expressed in several sets of larval muscles and in the CNS in each segment, and perhaps in adepithelial cells associated with the thoracic discs.

The leg and wing disc progenitor cells can be distinguished on the basis of gene expression and position before they become morphologically distinct from the larval ectoderm. Cells that will give rise to the wing and haltere discs derive from groups of about 30 cells that express Vg protein in the second and third thoracic segments at about 10 hours of embryogenesis (grey, Fig. 1B). When the wing and haltere discs invaginate, they contain approximately 24 and 12-15 Vg-expressing cells respectively, in good agreement with the numbers reported by Bate and Martinez-Arias (1991) based on histochemical staining. It is possible that the initial expression of Vg in clusters of approx. 30 cells may reflect an initially broad domain of expression that resolves as the disc invaginates. At 10 hours the clusters of Vg-expressing cells are separated by 3-5 cells from the leg primordia, which express Dll.

Early expression of Dll may provide a molecular marker for allocation of thoracic imaginal cells

Since the imaginal discs originate as distinct anterior and posterior founder populations which flank the parasegment boundary in the embryo, we have suggested that allocation of these cells may depend on intercellular signals transmitted by the secreted Wingless (Wg) protein (Simcox et al., 1989; Cohen, 1990). Wg protein can be detected over a range of 2-3 cells flanking the cells that express wg transcript (van den Heuvel et al., 1989; González et al., 1991). Dll is expressed in a cluster of cells which is symmetrically distributed around the row of cells expressing wg (Cohen,
By using mutations in segment polarity genes to manipulate the anterior-posterior pattern of the embryonic segment, it has been possible to show a compelling correlation between the pattern of wg and Dll expression in the segment and the resulting anterior-posterior pattern of the leg discs (Simcox et al., 1989; Cohen, 1990). This correlation suggests that early expression of Dll responds to the same positional signals that specify the identity of the presumptive imaginal cells. As such, Dll expression may provide a useful marker with which to monitor the allocation process.

Dll is expressed in clusters of cells surrounding the ends of the ventromedial wingless stripes in the trunk segments of 5-5.5-hour old embryos (Cohen, 1990). The observation that Dll expression is restricted to a well defined position on the wg stripe suggests that a dorsal-ventral positional cue is required in addition to the Wg signal. Based on its pattern of expression, the decapentaplegic (dpp) gene is a good candidate to provide the second signal. dpp encodes a secreted signalling molecule of the TGF-β family (Padgett et al., 1987). dpp is expressed in longitudinal stripes running the length of the embryonic trunk region (St. Johnston and Gelbart, 1987; Blackman et al., 1991) at the time when Dll is first expressed. Double-labelling studies show that the rows of cells that express wg and dpp abut one another in each segment, forming a ladder-like pattern (Fig. 2A,B).

In order to trace the early stages of development of the disc primordia we have made use of an early-acting Dll cis-regulatory control element (known as Dll-304) to direct expression of a lacZ reporter gene in the leg primordia. Double-labelling studies show that the Dll-304 transgene is expressed as early as the endogenous Dll gene and in a spatially correct pattern (see Vachon et al., 1992 and Fig. 6A). The Dll-304 transgene is activated in clusters of cells which overlap the intersection points between the two rows of cells expressing wg and dpp (Fig. 2C). The Dll-304 transgene is activated in cells near the intersection point that express wg or dpp and also in nearby cells that do not express either of these genes. Although the Dll enhancer is activated symmetrically about the stripe of wg-expressing cells, the cluster is somewhat wedge shaped. At the dorsal side, cells farther from the stripe of wg-expressing cells activate the enhancer. These cells are closer to the dpp-expressing cells (which are adjacent to the wg-expressing cells but which do not overlap them). Similarly, cells closer to the source of the wg signal on the ventral side can be farther from the stripe of cells expressing dpp. We observe a similar, though less pronounced wedge shape in the pattern of expression of the endogenous Dll protein (Fig. 2D).

The spatial relationship between the cluster of cells in which the Dll enhancer is activated and the locations of the cells expressing wg and dpp suggests that cells that sense adequate concentrations of both secreted proteins might be signalled to activate the early enhancer. Thus the rows of cells that express wg and the rows of cells that express dpp might be viewed as part of an orthogonal co-ordinate system used to position the leg primordia with respect to anterior-posterior and dorsal-ventral pattern in the segment.

**Activation of the early Dll enhancer correlates with the temporal requirement for wingless activity in allocation of the imaginal primordia**

The early Dll enhancer element is only transiently activated in the leg primordia. Although the endogenous Dll gene continues to be expressed in the leg primordia throughout embryogenesis (Fig. 3A,B), the lacZ RNA encoded by the transgene decays during germ band retraction (Fig. 3C,D).

---

**Fig. 1. Molecular markers for the leg and wing primordia.**

(A) Late embryo (approx. stage 15) carrying the Dll-215 late enhancer transgene. The embryo was double labelled with antibodies to vestigial (Vg) protein and anti-β-gal. The pattern of Vg-expressing cells (grey) is complex in the late embryo. The wing and haltere imaginal discs can be seen as sacs of cells invaginating from the ectoderm in the second and third thoracic segments (arrows). Vg also labels several sets of larval muscles and the CNS (not shown). The leg discs (arrowheads) express β-gal protein under control of the Dll enhancer (brown). A band of muscle running between the leg discs and the wing and haltere discs is labelled (M). This Fig. is shown to indicate the relative locations of the dorsal and ventral discs primordia late in embryogenesis (for comparison with Fig. 7). (B) Germ band retracted embryo (late stage 12) double labelled for β-gal activity (blue) and by antibody to Vg. The leg primordia in the thoracic segments (t1-t3) are labelled by β-gal expression. The primordia of the wing and haltere discs express Vg (grey, arrows). These clusters are separated from the leg primordia by only about 3-5 cells at their nearest points.
Like the endogenous gene, expression of the \( Dll \) early enhancer transgene is \( wg \)-dependent (data not shown). The observation that the early enhancer is only transiently active raised the possibility that \( Dll \) expression in the embryo might depend on \( wg \) only during the time when the early enhancer was functional. To test this proposal we used the temperature-sensitive allele, \( wg^{IL114} \) to assess the effects of functionally inactivating Wg protein at different stages during specification of the imaginal primordia. The Wg protein encoded by the \( wg^{IL114} \) allele has normal activity at the permissive temperature (18°C) and appears to have no activity at the restrictive temperature (29°C; Baker, 1988; Heemskerk et al., 1991; Bejsovec and Martinez-Arias, 1991). \( wg^{IL114} \) embryos were allowed to develop at 18°C and were shifted to the restrictive temperature at intervals before, during and after the activation of the \( Dll \) early enhancer. \( Dll \) is not expressed in the leg primordia of \( wg^{IL114} \) embryos raised continuously at the restrictive temperature (not shown).

To identify the latest stage at which \( Dll \) expression in the leg primordia remained \( wg \)-dependent, we staged the embryos with respect to their pattern of \( Dll \) expression at the time of the shift to the restrictive temperature. A subset of the embryos in each collection were fixed when their siblings were shifted to the restrictive temperature. Embryos allowed to develop for 7-8 hours at 18°C had, on average, just begun to express \( Dll \) in the leg primordia (Fig. 4D, arrows; these embryos were allowed to develop for 8-9 hours at 18°C, equivalent to 5-5.5 hours at 25°C). Mutant embryos shifted to the restrictive temperature at this stage are less sensitive to removal of \( wg \) activity, and continue to show...
some Dll expression at later stages. Within this tightly staged population there is a discernible difference between the oldest and youngest embryos. The youngest mutant embryos in the population show no Dll expression (as in the younger population described above). We could not detect any difference between the oldest mutant embryos in the population and their wg* siblings (these embryos had completed germ band retraction at the time of fixation). Embryos of intermediate age had not quite finished germ band retraction at the time of fixation and showed reduced level of Dll expression (arrows, Fig. 4E; comparably aged control sibling, Fig. 4F). The embryo in E is typical of the oldest mutant embryos in which we could detect a significant reduction of Dll expression. Based on the age distribution in the population at the time of the shift to the restrictive temperature, we conclude that these embryos had just begun to detectably express Dll protein in the leg primordia when Wg protein was inactivated. Once Dll protein is present, there is little effect of removing Wg function.

Dll remains dependent on Wg activity until the early enhancer has been activated and then rapidly becomes independent of further signalling from Wg. Interestingly, Baker (1988) has shown that Wg activity is not required until 4-5 hours of embryogenesis to specify the Keilin’s organs (and therefore presumably Dll expression, since development of the Keilin’s organs depends on Dll gene activity; Cohen and Jürgens, 1989). These observations suggest that the signal to activate Dll is transmitted during a relatively brief time interval at about 5-5.5 hours of embryogenesis. The time interval, during which the Wg signal appears to be transmitted to Dll, correlates well with the time at which the wg and dpp expressing cells are arranged in the ladder-like pattern.

Does the temporal requirement for Wg activity in activating Dll correspond to the temporal requirement for Wg in allocation of the imaginal primordia? We made use of a molecular probe from the escargot (esg) gene to monitor the development of the imaginal primordia in a second set of wingless temperature shift experiments. esg transcript is expressed in imaginal cells of the thoracic, genital and cephalic discs beginning at stage 13 of embryogenesis (Whiteley et al., 1992; Hartenstein and Jan, 1992). The specification of the thoracic imaginal cells shows precisely the same temporal dependence on Wg activity that we observed for Dll expression. Embryos shifted to the restrictive temperature before 5 hours (25°C) lack thoracic imaginal disc primordia (Fig. 4G). Their Wg* siblings show well developed dorsal and ventral thoracic discs (Fig. 4H). The genital and cephalic disc primordia appear to be unaffected by removal of Wg activity. The embryos in this population were of the same age as the embryos in Fig. 4A-C at the time of the temperature shift. Embryos shifted to the restrictive temperature after Dll was activated in the legs were insensitive to the removal of Wg activity and developed normal thoracic discs (assessed by esg staining, data not shown).

These observations suggest that the dorsal and ventral thoracic imaginal primordia are allocated in response to a Wg-dependent signal at approximately 5 hours of embryogenesis. They also suggest that expression of Dll in the leg primordia may be initiated in response to the same signals that are responsible for allocation of the imaginal primordia. Additional support for this suggestion derives from following the developmental fate of cells that first express Dll in response to the Wg signal.

**A group of cells leaves the leg primordium during germ band retraction**

The ladder-like arrangement of cells expressing Wg and dpp only exists for a relatively short time in the germ band extended embryo. During germ band retraction the row of
602 B. Cohen, A. A. Simcox and S. M. Cohen

cells that express dpp is displaced dorsally, away from the wg stripe (Fig. 5A,B). As this occurs, a subset of the cells, which expressed β-gal protein under control of the early Dll enhancer (β-gal+ cells), also separate from the ventral cluster. The dorsal-most group of these cells appear to remain aligned with the cells that express dpp in the longitudinal stripe (black arrow, Fig. 5B), while the ventral cluster remain centered on the end of the wingless stripe (white arrow, Fig. 5B). For comparison, a double label showing the location of the leg primordia and the dorsally displaced stripe of dpp expression is shown in Fig. 5C. The leg primordia are labelled by β-gal expression directed by the late acting Dll enhancer transgene (blue). The late acting Dll enhancer is turned on somewhat after the early enhancer in cells of the leg primordia (which initially express Dll under control of the early enhancer). Note that cells labelled later do not show the extensive dorsal displacement seen in the cells that are labelled at an earlier stage by expression of the early enhancer.

The dorsal displacement of β-gal+ cells is not a reflection of the normal pattern of lacZ mRNA expression directed by the early enhancer. β-gal protein is quite stable and persists in these cells long after the lacZ mRNA has decayed (see Fig. 3C-F for a comparison of the stability of lacZ RNA and β-gal protein). The β-gal+ cells in the dorsal extension must have originated in the ventral cluster of cells that expressed the Dll-304 transgene in the germ band extended embryo. The perdurance of β-gal protein provides a long-lived molecular label which allows us to observe the dorsal displacement of these cells.

To assess the relationship between the β-gal+ cells (in which the early enhancer was active) and the cells of the

Fig. 4. Dll expression and allocation of the imaginal primordia depend on wingless activity at about 5 hours of embryogenesis. (A-C) Embryos allowed to develop at 18°C for 7-8 hours at 18°C before the shift to the restrictive temperature. (A) Representative embryo fixed at the time of the shift to 29°C. Dll protein is not yet detectable in the leg primordia of these embryos (arrows). (B) wgIL114 mutant embryo fixed 3 hours after shift to 29°C. Dll is absent from the leg primordia (arrows), although it continues to be expressed in the head. (C) Dll is abundant in the leg primordia of a heterozygous sibling embryo (of comparable age to the mutant in C). (D-F) Embryos allowed to develop at 18°C for 8-9 hours at 18°C before the shift to the restrictive temperature. (D) Dll protein is just becoming detectable in the leg primordia of embryos fixed at the time of the shift to 29°C (arrows). (The appearance of the endogenous Dll protein is somewhat delayed with respect to the transcriptional activation of the Dll-304 element. β-gal protein expressed by Dll-304 is detectable earlier than the endogenous Dll protein in double-labelling experiments, data not shown). (E) wgIL114 mutant from this pool fixed 3 hours after shift to 29°C. This embryo is typical of the oldest affected mutant embryos that we observed. The level of Dll protein is much reduced in the legs of the mutant, as compared to their heterozygous siblings (shown in F). No difference could be detected between mutant and wild-type embryos that were older than the embryo shown in E (i.e. fully germ band retracted). Since the oldest mutant embryos in the population no longer show any defect in Dll expression, the proportion of affected embryos is smaller in the group shifted between 8-9 hours than in the group shifted between 7-8 hours. wg activity appears to be required until Dll is turned on via the early enhancer. (G,H) Embryos were collected, aged and shifted to the restrictive temperature as in A-C. The age at the time of the shift to 29°C was verified by Dll expression (not shown). The embryos were aged for 7 hours at 29°C and labelled to visualize escargot RNA by in situ hybridization. (G) wgIL114 mutant embryos from this pool lack dorsal and ventral thoracic discs. The genital (G) and cephalic (C) imaginal primordia are not affected. (H) Heterozygous sibling embryo. The plane of focus is on the dorsal thorax to show the prothoracic (P), wing (W) and haltere (H) discs. The prothoracic disc is associated with the anterior spiracle. The leg discs are visible, but out of focus, at the ventral edge of the embryo in the thoracic segments. Note that head involution fails in the mutant embryos, so the cephalic imaginal cells have not migrated as far to the anterior in G, as in the control sibling in H.
Martinez-Arias (1991) have reported that the region between the leg and wing discs shows a locally high level of proliferation between 5 and 11 hours of embryogenesis. The posterior region of the segment shows strongest labelling, consistent with a role for local cell division in the dorsal displacement of β-gal+ cells in the posterior part of the segment.

**Wing and haltere precursor cells derive from the ventral cluster**

The dorsal-most group of the displaced β-gal+ cells come to lie the region in which the wing and haltere imaginal disc primordia can first be morphologically detected. As shown in Fig. 1, the invaginating discs have a distinctive appearance and can be readily identified in flattened preparations of approx. 12-hour old embryos. On morphological grounds, the dorsal-most group of β-gal+ cells appear to invaginate to form the wing and haltere imaginal discs (Fig. 6C). To confirm that the β-gal+ cells were in fact contributing to the forming dorsal discs we performed double labelling using antibodies to Vg protein and β-gal (Fig. 7). Vg (red) and β-gal (green) proteins are co-expressed in the invaginating wing and haltere discs of transgenic embryos, which therefore appear yellow. These observations indicate that cells that contribute to the formation of the dorsal imaginal discs expressed the Dll early enhancer transgene some hours earlier in the germ band extended embryo. These cells appear to originate together with the cells of the presumptive leg in a ventrally located cluster of cells in which the Dll early enhancer element is active. A subset of the presumptive imaginal cells are displaced dorsally. After separating from the ventral cluster, these cells begin to express Vg and subsequently invaginate to form the wing and haltere discs.
**Dll is not required for specification of the imaginal primordia**

The observation that both dorsal and ventral disc primordia develop from cells that expressed the Dll early enhancer raised the possibility that Dll plays a role in allocation of the imaginal primordia. To address this issue, Dll null mutant embryos were cultured in the abdomens of female flies by transplantation of embryo fragments. In vivo culture allows the imaginal discs to be rescued from embryos carrying lethal mutations, if the mutation does not interfere with growth of the disc cells (as described in Simcox et al., 1989). Dll null mutant embryos produced both leg and wing imaginal discs following in vivo culture, indicating that although the discs originate from a population of Dll-expressing cells in the embryo, Dll gene activity is not required for the allocation of the disc primordia.

To assess their developmental potential, Dll mutant imaginal discs were transplanted into wild-type larvae and induced to undergo metamorphosis. Leg and wing discs were recovered with equal frequency from wild-type and from Dll null-mutant embryos following embryo culture (Table 1). Leg discs from Dll mutant embryos produced structures characteristic of the ventral thoracic body wall and coxa. No structures from the trochanter, femur, tibia or tarsal segments of the leg were recovered from mutant discs (Fig. 8). Control discs, cultured from wild-type embryos, produced a range of structures characteristic of all of the major leg segments (Table 1). These findings are consistent with previous clonal analysis (Cohen and Jürgens, 1989) and indicate that Dll is required in only a subset of cells in the leg disc primordium to distinguish the presumptive leg cells from the surrounding body wall.

**DISCUSSION**

**When does allocation of the imaginal progenitor cells occur?**

Early studies on the determination of the imaginal cells in the embryo suggested that the imaginal primordia are determined at the blastoderm stage (Chan and Gehring, 1971;
expressing cells in a late embryo imaged using a confocal microscope. The invaginated wing (W) and haltere (H) discs contain both proteins and appear yellow. The second (L2) and third leg (L3) discs contain β-gal and label green. Note the band of muscle cells (red) between the legs and wing/haltere discs (compare with Fig. 1). B and C show the individual images of the Dll-β-gal expressing cells form the wing and haltere discs. (A) Immunofluorescent localization of β-gal (green) and vestigial (red) expressing cells in a late embryo imaged using a confocal microscope. The invaginated wing (W) and haltere (H) discs contain both proteins and appear yellow. The second (L2) and third leg (L3) discs contain β-gal and label green. Note the band of muscle cells (red) between the legs and wing/haltere discs (compare with Fig. 1). B and C show the individual images of the Vg and β-gal labellings that were merged to make the image in A.

Simcox and Sang, 1983). However, a recent set of experiments by Meise and Janning provides compelling evidence to the contrary. Meise and Janning (1991) transplanted single blastoderm cells from a donor embryo, which expressed β-gal in all cells, into a wild-type host embryo at the blastoderm stage and monitored the fate of the clonal progeny of the injected cell. A single cell injected at the blastoderm stage can contribute to both an imaginal disc and to the larval hypoderm. These experiments clearly demonstrate that there is no lineage restriction between larval and imaginal ectoderm at the blastoderm stage, and therefore indicate that the imaginal cells cannot have been allocated at the blastoderm stage.

The formation of imaginal primordia in the thoracic segments requires the function of the wingless gene (Simcox et al., 1989). Using a temperature-sensitive wg mutation, we have shown that wg activity is required at approximately 5-5.5 hours of embryogenesis for the subsequent development of the discs. At this time wg and dpp are expressed in a ladder-like arrangement in the ectoderm. We suggest that allocation of the thoracic imaginal progenitor popula-

**Table 1. Structures produced by Dll mutant leg imaginal discs**

<table>
<thead>
<tr>
<th>Genotype (n)</th>
<th>Wing including coxa</th>
<th>Trochanter</th>
<th>Distal leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dll/Dll (11)</td>
<td>9 (82)</td>
<td>10 (90)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>+/- (5)</td>
<td>4 (80)</td>
<td>4 (80)</td>
<td>4 (80)</td>
</tr>
<tr>
<td>+/- (5)</td>
<td>4 (80)</td>
<td>5 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>+/- (5)</td>
<td>4 (80)</td>
<td>5 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>+/- (5)</td>
<td>4 (80)</td>
<td>5 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>+/- (5)</td>
<td>4 (80)</td>
<td>5 (100)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

The different regions of the leg can be characterized by the types of sensory structures that they produce. These have been described in detail for the first leg (11). Although different in some details, the overall pattern of sensory structures for second and third leg are similar. Groups of sensilla trichodea (st) are found on the coxa (st8, st4, st3) and on the trochanter (GST, st5, st1). The trochanter also has groups of sensilla campaniforma (sc) which are not found on the coxa. Distal leg segments are most easily characterized by the presence of bracted bristles, and in some cases by the claw. Ventral body wall and coxa were identified by the presence of sternopleural bristles (for T2 legs), st8, st4 and st3 (for T1 legs) and the absence of sc groups. Trochanter was identified by the presence of 2 GST groups, sc3, a large sc group, st1 and st5. In the Dll mutant legs coxa structures were clearly identified in all cases. No GST groups, sensilla campaniforma groups, or bracted bristles were seen indicating the absence trochanter and distal leg structures. Bracted bristles were seen in all control legs indicating the presence of distal leg segments. In 4 of the control legs characteristic coxa and trochanter structures were identified. Although st groups were identifiable in the 5th control leg, it was not possible to score the more proximal leg structures unambiguously because the proximal segments of the disc were obscured by more distal tissue.

**Does dpp co-operate with wg in specification of the thoracic imaginal primordia?**

On theoretical grounds, Meinhardt (1983) proposed that the imaginal disc primordia would be established in a naive field of cells in response to a secreted morphogen. He proposed that localized production of the morphogen would result from interaction between cells that derive from adjacent compartments in the embryonic segment. A more recent version of this model invokes the overlap between a secreted A/P morphogen and a secreted D/V morphogen to specify the limb field (Meinhardt, 1991). Our data suggest that the relevant positional information is transmitted by the combined input from two molecularly distinct intercellular signals, the Wingless and Dpp proteins. These observations are compatible with the basic premise of Meinhardt’s model that the interaction between cells with different properties would provide the signal to allocate the imaginal primordia.
We have shown previously that the (secreted) wg signal is required for Dll expression and specification of the imaginal primordia (Simcox et al., 1989; Cohen, 1990). Similarly, dpp activity is required for expression of Dll in the leg primordia (B.C. unpublished data). However, since dpp null mutants cause dramatic ventralization of the embryo, we cannot yet determine whether the absence of Dll expression reflects a direct requirement for dpp in activating Dll or whether the disc primordia have indirectly been shifted off the fate map (Irish and Gelbart, 1987; Ray et al., 1991). Like dpp, tolloid is required for dorsal-ventral patterning and encodes a member of the TGF-β family (Shimell et al., 1991). tolloid expression overlaps dpp in the lateral stripes which make up the ladder. However, tolloid function is not required for activation of Dll in the imaginal primordia (data not shown).

Although we do not yet know whether dpp serves as the direct source of a positional signal, the combination of the Wnt and TGF-β (or other) signals is, in principle, sufficient to specify the identity of the leg precursor cells. The use of two secreted signalling systems would provide an elegant mechanism with which to allocate groups of cells to the disc founder populations, based on their locations in the embryonic ectoderm. There is no reason a priori why the second ‘line’ need be encoded by a secreted signalling molecule. However, we favor this proposal because of the detailed spatial relationship between cells expressing Dll, wg and dpp. The use of two secreted signals provides a plausible model to explain the wedge shape of the cluster of cells that activate the early enhancer (Fig. 9). We can account for the wedge shape of the cluster if we assume that a higher concentration of one signal can make up for a slightly reduced level of the other signal. In this way cells close to the source of the wg signal require slightly less of the dpp signal to activate the enhancer, leading to a narrowing of the cluster toward its ventral side. Similarly cells closer to the source of the dpp signal require slightly less of the wg signal, leading to a broadening of the cluster along its dorsal side (Fig. 9).

One set of signals for allocation of dorsal and ventral discs

Our description of the origin of the dorsal disc primordia confirms previous genetic studies which suggest that the dorsal and ventral discs originate in close proximity. Using a molecular lineage tag, we have shown that the leg and wing discs originate within a cluster of cells that expressed Dll in the early embryo. The cluster of Dll-expressing cells is aligned with the intersection of the stripes of wg and dpp-expressing cells. Formation of both dorsal and ventral discs depends on wg activity at this time. As the germ band retracts, the stripes of cells expressing wg and dpp separate. The presumptive dorsal disc cells remain aligned with the dpp stripe during this movement, while the progenitors of the leg disc remain aligned with the end of the ventromedial wg stripe (Fig. 9). An appealing feature of this model is that only one set of positional cues is required for allocation of both dorsal and ventral thoracic discs.

Similar observations on the separation of dorsal and ventral discs have been reported by Anderson (1963) from studies on the Queensland fruit fly, Dacus tyroni. According to Anderson the wing and haltere discs originate as part of the leg discs, from which they become separated during embryonic development by local cell division. The leg and wing discs are physically connected by a stalk in the mature Dacus embryo. Dorsal migration of the wing precursors seems to be typical of all winged insects, not only of diptera. The wings migrate away from the legs in a dorsal and posterior direction during successive moults in a variety of hemimetabolous insects. In primitive paleo-insects the wing was moved by muscles connected to the leg (see Kukalova-Peck, 1978 for descriptions and discussion).
Do leg and wing derive from a common imaginal primordium?

Gynandromorph analysis has suggested that the dorsal and ventral disc primordia originate in very close proximity (Wieschaus and Gehring, 1976a). The observation that the spacing between markers on the two discs can be closer than the separation between some markers within one disc suggests that the primordia derive from an overlapping population of progenitor cells. Are the dorsal and ventral discs genetically distinct entities at the time of their allocation? The data presently available from analysis of genetic mosaics do not allow us to answer this question. The dorsal and ventral discs have been shown to share common progenitors prior to allocation. Clones of cells, marked by X-ray induced mitotic recombination during the cell division following the blastoderm stage, can contribute to both leg and wing disc primordia (Wieschaus and Gehring, 1976b; Steiner, 1976; Lawrence and Morata, 1977). Clones produced one cell division later are restricted to either the dorsal or ventral discs. The limited number of post-blastoderm cell divisions restricts the production of mosaics after allocation of the imaginal cells. Consequently, clonal analysis has not distinguished whether the dorsal and ventral discs originate as a common primordium or as genetically distinct but adjacent primordia.

We have shown that the cluster of cells expressing the early Dll enhancer contains imaginal disc progenitor cells for both the dorsal and ventral discs. This observation demonstrates that at least one aspect of the molecular identity of this population appears to be specified by the combination of wg and dpp signals. We have also shown that it is not possible to distinguish between the time at which wg gene activity is required for allocation of the imaginal primordia and for initiation of Dll expression. This conclusion does not imply that Dll has any role in allocation. Nonetheless, expression of the Dll enhancer shows that this population can be signalled as a group to adopt a particular molecular identity. Although we cannot exclude the possibility that there might be genetically distinct dorsal and ventral imaginal sub-primordia within this cluster, we suggest that the simplest explanation for our data and for the genetic mosaic studies lies in a common imaginal primordium.

We thank Fernando Diaz-Benjumea for discussions about the manuscript; Elaine McGuffin and Christine Pfeifle for technical assistance; Jim Williams and Sean Carroll for the vestigial antibody; Juan Botas for the CyO, Dp y* balancer chromosome and advice on fluorescence microscopy; Louis Smith of the Department of Medicine, Baylor College of Medicine for use of his confocal microscope and Judi Cooper for secretarial assistance. This work was supported by the Howard Hughes Medical Institute and by Basil O’Connor Starter Scholar Research award no. 5-91-510 to S. C.
REFERENCES


(Accepted 6 November 1992)