A *Drosophila* growth factor homolog, *decapentaplegic*, regulates homeotic gene expression within and across germ layers during midgut morphogenesis

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Summary

The *decapentaplegic* (*dpp*) gene product, a member of the transforming growth factor-β family, is required in *Drosophila* embryos for normal gastrulation and the establishment of dorsal-ventral polarity in the embryo. *dpp* is also expressed at specific positions in the visceral mesoderm along the developing midgut. We find that mutations that eliminate the visceral mesoderm expression of *dpp* lead to defects in midgut morphogenesis and alter the spatially localized expression of the homeotic genes *Sex combs reduced* (*Scr*), *Ultrabithorax* (*Ubx*), and *Antennapedia* (*Antp*) in the visceral mesoderm. The extracellular *dpp* protein migrates from the visceral mesoderm across the opposing endodermal cell layer in a region of the endoderm that expresses the homeotic gene *labial* (*lab*). Mesodermal expression of *dpp* is required for the expression of *lab* in these endodermal cells indicating that *dpp* mediates an inductive interaction between the two germ layers. We propose that extracellular *dpp* protein regulates gut morphogenesis, in part, by regulating homeotic gene expression in the visceral mesoderm and endoderm of the developing midgut.

Key words: *decapentaplegic*, *Ultrabithorax*, *Sex combs reduced*, *Antennapedia*, *abdominal A*, *labial*, visceral mesoderm, endoderm.

Introduction

The final stages of midgut development in the *Drosophila* embryo involve the migration and stretching of cells in two distinct germ layers to enclose the yolk. The inner endodermal layer is composed of large polyplloid cells, while the outer visceral mesoderm layer is composed of small euploid cells. The double-walled gut tube is then compartmentalized into four morphologically distinct chambers and four caeca, long appendages extending from the anterior end of the midgut tube. The four chambers of the midgut are created when three constrictions form at specific positions along the length of the midgut. The caeca are formed as buds off the anterior end of the midgut which elongate and extend into the head regions of the embryo. In the final stages of embryogenesis, the compartmentalized midgut stretches out to form a long convoluted tube (Poulson, 1950; Campos-Ortega and Hartenstein, 1985; Reuter and Scott, 1990). The specific roles in gut function of the four midgut chambers are not known.

Four homeotic genes expressed in the visceral mesoderm of the midgut are crucial for gut morphogenesis (Tremml and Bienz, 1989a; Reuter and Scott, 1990). *Scr* is expressed in the visceral mesoderm cells at the anterior end of the midgut immediately posterior to the budding gastric caeca. In the absence of *Scr* expression, the gastric caeca do not develop properly (Reuter and Scott, 1990). Adjacent and posterior to the domain of *Scr* expression is a domain of *Antp* expression. *Antp* is expressed by visceral mesoderm cells surrounding the first constriction and, in the absence of *Antp* expression, the first constriction does not form (Tremml and Bienz, 1989a; Reuter and Scott, 1990). Immediately posterior to the *Antp* domain is a domain of *Ubx* expression. *Ubx* is expressed in the visceral mesoderm cells of the anterior half of the second constriction with expression extending anteriorly toward the first constriction. In the absence of
Ubx expression, the second constriction does not form (Bienz and Treml, 1988; Treml and Bienz, 1989a; Reuter and Scott, 1990). Immediately posterior to the Ubx domain, abdominal A (abaA) is expressed in the visceral mesoderm cells of the posterior midgut. The anterior limit of the abaA domain is the posterior half of the second constriction and includes the region around the third constriction. Without abaA function, neither the second nor the third constrictions form (Treml and Bienz, 1989a). The mechanisms by which these four homeotic genes influence the formation of the constrictions are not known, nor is it clear whether constriction formation is driven by the mesoderm formed through the actions of both germlayers. Constriction formation is associated with the elaboration of extensive microtubular arrays in the visceral mesoderm cells at the site of the constriction (Reuter and Scott, 1990).

The molecular mechanisms regulating the domains of homeotic gene expression in the visceral mesoderm are not known. The expression domains of the four homeotic genes in the visceral mesoderm of the developing midgut are non-overlapping (Treml and Bienz, 1989a). This is in contrast to the expression patterns in the embryonic ectoderm where the Antp domain extends posteriorly through those of Ubx and abaA, and the Ubx domain extends posteriorly through that of abaA (Carroll et al. 1988; Karch et al. 1990). The regulatory interactions between the homeotic genes in the visceral mesoderm differ from the regulatory interactions observed between homeotic genes in the ectoderm. For example, Antp negatively regulates Scr in the ectoderm (Riley et al. 1987), but positively regulates Scr in the visceral mesoderm (Reuter and Scott, 1990). The pair rule gene fuz is required for activation of Scr, Antp, and Ubx expression in the ectoderm (Ingham and Martinez-Arias, 1986) but has little effect on the expression of these genes in the visceral mesoderm (Treml and Bienz, 1989b). It seems likely that the regulation of homeotic gene expression in the visceral mesoderm involves genes other than those used in the ectoderm. Genes that are expressed in specific patterns in the visceral mesoderm are good candidates for genes that may participate in the regulation of homeotic gene expression in the visceral mesoderm.

One gene expressed in specific regions of the developing midgut is the Drosophila decapentaplegic (dpp) gene, a member of the transforming growth factor-β (TGF-β) family (Padgett et al. 1987; Reviewed by Hoffmann, 1990). The visceral mesoderm expression of dpp was originally noted in the initial characterization of dpp’s embryonic expression (St. Johnston and Gelbart, 1987). During our studies on dpp expression in wild-type and mutant embryos using in situ hybridization to whole embryos (Tautz and Pfeiffer, 1989), we noted that one domain of dpp expression in the midgut visceral mesoderm appears to be coextensive with the reported parasegment 7 domain of Ubx expression in the midgut visceral mesoderm (Jackson and Hoffmann, in preparation). Our subsequent investigations are the subject of this report and a companion article (Reuter et al. 1990).

dpp is required for normal gastrulation and dorsal-ventral polarity in the Drosophila embryo (Irish and Gelbart, 1988). Its patterns of embryonic expression bear little resemblance to the anterior to posterior organization of the major patterns of homeotic gene expression. Rather, the ectodermal expression of dpp is regulated along the dorsal to ventral axis of the embryo beginning with a dorsally restricted stripe of dpp mRNA at cellular blastoderm (St. Johnston and Gelbart, 1987; Jackson and Hoffmann, in preparation). Midway through embryogenesis, dorsal and lateral stripes of dpp mRNA are detected which extend along the anterior–posterior axis through all the thoracic and abdominal segments. dpp null mutant embryos exhibit a transformation of dorsal and lateral hypoderm to ventral hypoderm, the most completely ventralized phenotype observed to date in the Drosophila embryo. Mutations that affect the 5' regulatory sequences, a region of five alternate dpp promoters called the shortvein region, give rise to embryos with normal dorsal-ventral polarity, but the animals die as larvae with some visible defects in internal organs (Segal and Gelbart, 1985). dpp mutations affecting 3' regulatory sequences, called the disk region, undergo normal embryogenesis and larval development but display an array of defects in the adult cuticular structures derived from the larval imaginal disks (Spencer et al. 1982; St. Johnston et al. 1990; Masucci et al. 1990).

Biochemical analysis of dpp protein produced in cultured Drosophila cells has indicated that dpp, like the other members of the TGF-β family, forms a dimer that is proteolytically processed and secreted from cells (Panganiban et al. 1990). Members of the TGF-β family have been shown to exert a wide variety of effects on cell proliferation, cell differentiation, extracellular matrix elaboration and hormone secretion (Roberts and Sporn, 1988). The effects of any specific factor in the family can vary depending on the target tissue and the dose. While the importance of TGF-β to wound healing has been well established, the roles of these factors in development are less well characterized. Several of the factors are expressed in a tissue specific fashion in developing mouse skin and bone, leading to the hypothesis that members of the TGF-β family establish regulatory cascades of interactions during sequential steps in the development of these tissues (Lyons et al. 1989a). Probably the most pertinent observation about the developmental role of a member of the TGF-β family is the regulation of the Xenopus homeotic gene xhox-3 by a Xenopus TGF-β homolog, XTC-MIF (Ruiz i Altaba and Melton, 1989). XTC-MIF induces animal cap cells to become mesoderm and induces xhox-3 expression to a level that determines an anterior mesodermal fate. A different growth factor, fibroblast growth factor, also induces mesoderm, but establishes higher levels of xhox-3 expression which gives rise to posterior mesoderm. Therefore the presence of a growth factor can specify the positional fate of cells through the regulation of homeotic gene.
We find that a *Drosophila* member of the TGF-β family, *dpp*, also regulates homeotic gene expression. *dpp* negatively regulates the homeotic gene *Scr* and positively regulates the homeotic gene *Ubx* in the visceral mesoderm cells of the midgut. Limited migration of *dpp* protein from the visceral mesoderm to the endoderm is required to induce expression of a third homeotic gene, *labial* (*lab*), in the endodermal cells. The expression of *dpp* in the visceral mesoderm is required for proper gut morphogenesis, specifically for the formation of the gastric caeca and the second midgut constriction. These same two features of gut morphogenesis require expression of *Scr* and *Ubx*, respectively.

**Materials and methods**

The *Antp*, *Ubx* and *Scr* mutant embryos used in these experiments were generated as described by Reuter and Scott (1990). *abd-A* mutant embryos were generated by homogygosing the *ahdA* allele (Sanchez-Herrero et al. 1985). The *dpp* alleles used in these experiments were isolated by Segal and Gelbart (1985). The molecular lesions associated with these mutations are summarized in Fig. 1C and were described by St. Johnston et al. (1990). To generate mutant embryos, balanced stocks of the various *dpp* alleles were outcrossed to wild-type Canton S females. *dpp*/*Canton S* virgins were then mated similarly outcrossed males carrying a different *dpp* allele. The embryos from these crosses were fixed and stained as described below. To avoid the possibilities that any defects observed were due to mutations other than *dpp* or to the genetic background in which a given *dpp* allele had been generated, each cross was performed with two *dpp* different alleles which had been induced on unrelated starting chromosomes.

*Scr*, *Ubx* and *Antp* antibodies used are described in Reuter and Scott (1990); *lab* antibodies are described in Diederich et al. (1989). Antibodies to *dpp* were generated as described by Panganiban et al. (1990). To affinity purify the resulting polyclonal antibodies, sera were first passed over Affigel protein A columns (BioRad) to purify the IgG. Sera were diluted with an equal volume of 1.5 M glycine; 3 M NaCl pH 8.9 prior to loading on the columns. The columns were washed with 5 volumes of this buffer prior to elution with 0.1 M glycine; 20 mM NaCl pH 3.2. IgG containing fractions were cut with 50% (final concentration) saturated ammonium sulfate, and centrifuged at 10,000 g to pellet the precipitate. The IgG was then dialyzed against PBS (10 mM KPO4, 140 mM NaCl pH 7.2) prior to loading on a *dpp* affinity column. *dpp* affinity columns were generated by coupling 5–10 mg of SDS–PAGE purified and electroeluted pG17 inclusion bodies (described in Panganiban et al. 1990) to 0.1 M MOPS pH 7.5 to Affigel 10 (BioRad) according to manufacturers' instructions. IgG fractions containing antibodies to *dpp* were loaded on the affinity columns at 5–10 ml h−1. The columns were washed extensively with 10 mM NaPO4 pH 7.0 to reduce the buffer concentration prior to elution with 0.1 M glycine pH 2.5. 1 ml fractions were collected directly into 100 μl of 1 M NaPO4 pH 8 to neutralize the glycine (Harlow and Lane, 1988). Antibody concentration was determined by absorbance at 280 nm (A280 of 1=0.56 mg ml−1). BSA (Sigma) was added to a final concentration of 1 mg ml−1 and sodium azide was added to 0.02% prior to storage at 4 or −20°C.

Embryos for immunohistochemistry were dechorionated, fixed and devitellinized using a modification of the methods of Mitchison and Sedat (1983). Briefly, embryos were dechorionated in 50% bleach for two minutes, rinsed with distilled water and fixed for 20 min in a two phase system composed of 1 part heptane and 1 part 4% paraformaldehyde in PBS (PF–PBS). The PF–PBS was then replaced with methanol, leaving the embryos at the interface. To devitellinize the embryos, the tubes were shaken gently until the majority of the embryos had settled through the methanol. The heptane and methanol were then removed with a pipette. Embryos were rinsed 3 times with absolute ethanol and treated with 3% hydrogen peroxide (in ethanol) for 1 min to inactivate endogenous peroxidases. For optimum staining with the *dpp* antibody, it was necessary to stain the embryos immediately following fixation. All other antibodies gave excellent staining with embryos fixed 3–6 months previously and stored at −20°C in ethanol. Antibody incubations and washes were modified from the methods of Carroll and Scott (1985). Embryos were rehydrated through a series of ethanol: PT (PBS plus 1% Triton X-100) 50:50; 25:75; 0:100 and blocked at least 3 h in PBT (PBS plus 0.2% BSA plus 0.1% Triton X-100) with 2% normal goat serum (Sigma). All subsequent washes and incubations were in PBT unless otherwise specified.

Primary antibodies were incubated with embryos overnight at 4°C. The *dpp* antibody was used at 1 μg ml−1; lab was used at 1:150; and *Scr*, *Antp* and *Ubx* monoclonals were used at 1:3, 1:5 and 1:5, respectively. At least 10 ml washes were carried out over 4–8 h after each incubation with antibody or with streptavidin–HRP. Secondary antibodies, biotinylated goat anti-rabbit IgG (Vector Laboratories) or HRP-conjugated goat anti-mouse IgG (BioRad), were preadsorbed against embryos and incubated with the embryos for 2 h at room temperature. Final dilutions in PBT plus 2% NGS were 1:1000 for the anti-rabbit and 1:400 for the anti-mouse. Washes were as described above. Embryos probed with the monoclonals were then developed in PBT; 0.25 mg ml−1 diaminobenzidine (Sigma); and 0.05% hydrogen peroxide (Sigma). Embryos probed with the *lab* and *dpp* antibodies were incubated for 1 h at room temperature with a 1:300 dilution of streptavidin–HRP (BRL) which had been preadsorbed against embryos. Embryos were then washed and developed as described above. Stained embryos were washed extensively with PBT and PBS, dehydrated through an ethanol series and cleared in methyl salicylate (Sigma). The embryos were then either mounted in salicylate or embedded in Epon 812–Araldite prior to observation by differential interference contrast optics on a Zeiss Axioshot. 6 μm sections were cut from embedded embryos using a Reichert-Jung Ultracut E.

Embryos for RNA *in situ* were fixed in formaldehyde and probed with a digoxigenin labelled *dpp* cDNA probe according to the procedures of Tautz and Pfeifle (1989). Hybridized RNA was visualized via use of an alkaline phosphatase conjugated antibody to digoxigenin using the Genius kit from Boehringer Mannheim Pharmaceuticals.

**Results**

*dpp* is expressed at specific locations along the developing gut

*dpp* RNA is expressed in six positions along the developing larval gut (Fig. 1A). *dpp* expression is first detected in the midgut visceral mesoderm at the beginning of germ cell shortening, stage 12 (Campos-Ortega and Hartenstein, 1985). By the time germ cell shortening is complete, six specific regions of *dpp* expression are detected along the gut tube. These
include expression in the ectoderm of the foregut and hindgut and in the visceral mesoderm of the midgut. The two spots of staining in the foregut ectoderm are within the anlage of the pharynx and the esophagus. The two principle regions expressing *dpp* RNA in the midgut are within the anlage of the gastric caeca and the site of the second midgut constriction. Low levels of *dpp* expression can also be detected at the site of the third midgut constriction although this expression is not visible in Fig. 1. This latter expression is under the control of different cis-regulatory elements than the elements required for the other two parts of *dpp* expression in the midgut (Jackson and Hoffmann, in preparation) and is not dealt with further in the present report. In addition, *dpp* is expressed by the ectoderm of the hindgut. The sites of *dpp* expression in the midgut correspond to regions that undergo morphological changes during development. For example, the caeca evaginate from the anterior end of the midgut and extend anteriorly well into the head. *dpp* expression in the gastric caeca is no longer detected when the caeca reach full extension at stage 17. The second midgut constriction occurs in the domain expressing *dpp* in the middle of the midgut. Double labelling experiments using antibodies to *dpp* and *Ubx* indicate that the *dpp* domain overlaps that of *Ubx* (Reuter et al. 1990). The domain expressing *Ubx* has been shown to correspond to a metameric unit of the embryo known as parasegment 7 (PS 7) (Trembl and Bienz, 1989a). *dpp* expression in PS 7 is maintained during the process of forming the gut tube and then declines. To determine whether *dpp* expression is required for the morphological events of midgut development, we examined gut morphogenesis in *dpp* mutant embryos.

**Mutations in the dpp shortvein region eliminate dpp expression in the gut**

Null mutations at *dpp* lead to severe defects in gastrulation and embryonic dorsoventral polarity making examination of gut morphogenesis in these embryos difficult. Mutations in the shortvein region of *dpp*, however, allow normal gastrulation and dorsal–ventral
Fig. 2. Midgut morphogenesis in \( dpp^{821}/dpp^{82} \) embryos stained with anti-Scr antibody. The domain of Scr expression is extended anteriorly in the \( dpp^{821} \) mutant embryo (C,D) compared to wild-type (A,B). In addition, the gastric caeca (c) arrest growth and fail to elongate and narrow, the second midgut constriction (2) does not form, and the first midgut constriction (1) is shifted posteriorly.

Fig. 3. Antp in a wild-type (A) versus \( dpp^{821}/dpp^{82} \) (B) embryo. In the wild-type embryo, Antp protein is found in the nuclei of the visceral mesoderm cells surrounding the first constriction (1) (A). In the \( dpp^{821} \) mutant embryo (B), the domain of Antp expression and the first constriction are shifted posteriorly to approximately the position where the second constriction forms (2) in the wild-type embryo. In addition, the Antp domain no longer extends on either side of the first constriction but is limited to the anterior portion of the first constriction in the \( dpp^{821} \) mutant.
Fig. 4. *Ubx* expression in wild-type (A and C) versus *dppe∥/dppe∥* (B and D) embryos. The predominant alterations in *Ubx* expression observed in *dppe∥* mutant embryos are a reduction in the level of *Ubx* protein in the cells which express it and/or a reduction in the number of cells expressing *Ubx*. Panels A and B show stage 15 embryos fixed and stained in the same tube. The level of *Ubx* protein is clearly reduced in the *dppe∥* embryo (B) when compared to that of the wild-type embryo (A). Panels C and D show late stage 16 embryos also fixed and stained in the same tube. There are fewer cells in the *dppe∥* embryo (D) expressing *Ubx* than in the wild-type control (C). Also note that the *Ubx* expression in the *dppe∥* embryos is no longer restricted to the anterior part of the constriction which forms in PS 7 (A and C), but extends both anteriorly and posteriorly from the constriction (B) or, more often, just posteriorly (D).

Fig. 6. *lab* protein in a wild-type embryo (A) is present in the polyploid endoderm nuclei between the first and second constrictions. No *lab* protein is detected in the endoderm nuclei of the *dppe∥* mutant embryo (B).
pattern formation to occur but lead to larval lethality associated with slow larval growth and visible defects in internal structures, especially the Malphigian tubules (Segal and Gelbart, 1985). We have examined embryos mutant for dpp\(^{short\text{vein}}\) (dpp\(^{\text{shve}}\)) alleles for expression of dpp (Fig. 1B).

The sve region consists of more than 20 kb of DNA located 5' to the coding region of the dpp gene (Fig. 1C). This region harbors four (of five known) promoters with their respective alternative 5' non-coding exons (St. Johnston et al. 1990). dpp\(^{shve}\) mutant embryos were generated by crossing two different alleles to avoid making other undefined lesions on the chromosomes homozygous. A mutant embryo, dpp\(^{22}\) / dpp\(^{shve}\), probed with a digoxigenin labeled dpp DNA probe is shown in Fig. 1B. dpp\(^{shve}\) mutant embryos retain the dorsally localized blastoderm expression of dpp and the dorsal and lateral stripes of dpp in the ectoderm, but lack dpp expression in the midgut and have severely reduced foregut expression. Embryos mutant for dpp\(^{shve}\) alleles which eliminate only promoters P4 and P5 (dpp\(^{22}\) and dpp\(^{shve}\)) retain some dpp expression along the foregut and at the caeca, however, all dpp\(^{shve}\) mutant embryos we have examined exhibit midgut defects similar to those described below. Presumably, a minimum level of dpp product is required for wild-type development of the visceral mesoderm. Other aspects of dpp embryonic function are also sensitive to the level of dpp product as indicated by the haploinsufficient characteristics of dpp (Spencer et al. 1982; Irish and Gelbart, 1987).

Absence of dpp affects Scr expression and development of the gastric caeca

Scr has been localized to the visceral mesoderm cells immediately posterior to the budding gastric caeca (Fig. 2A and B) (Tremml and Bienz, 1989a; Reuter and Scott, 1990). dpp is detected anterior to the Scr expressing cells in the visceral mesoderm of the budding caeca. Double labelling experiments have confirmed that dpp and Scr domains are non-overlapping (data not shown). Expression of both dpp and Scr in the anterior midgut is initially detected at stage 13 when the germ band is fully retracted. Scr expression persists through stage 17 while dpp expression in the caeca diminishes in stage 15 and is gone by the end of stage 16. In dpp\(^{shve}\) mutants, which have reduced dpp expression at the caeca, the domain of Scr expression is expanded anteriorly to encompass those visceral mesoderm cells that in wild-type embryos express dpp (Fig. 2C and D) indicating that dpp expression represses Scr expression in the visceral mesoderm cells that give rise to the gastric caeca. Caeca development is arrested in dpp\(^{shve}\) mutants: instead of extending anteriorly to form long narrow tubes, the caeca of dpp\(^{shve}\) mutants remain short and broad (Fig. 2C and D).

Absence of dpp affects Ubx expression and eliminates the second midgut constriction

In dpp\(^{shve}\) mutants, the second midgut constriction does not form but the first and third constrictions do form (Fig. 2C,D). Antp is expressed in the visceral mesoderm cells surrounding the first constriction of the midgut (Fig. 3A) (Tremml and Bienz, 1989a; Reuter and Scott, 1990), and Ubx is expressed in the visceral mesoderm cells of and anterior to the second constriction (Fig. 4A,4C) (Bienz and Tremml, 1988; Tremml and Bienz, 1989a; Reuter and Scott, 1990). dpp\(^{shve}\) mutant embryos exhibit a range of Ubx expression patterns. Most frequently, the domain of Ubx expression is narrowed than in wild-type embryos (Fig. 4D) or the levels of Ubx protein in expressing cells are greatly reduced (Fig. 4B). We have also observed dpp\(^{shve}\) mutant embryos in which both the level of Ubx and the number of cells expressing it are reduced (data not shown). In addition, the position of the Antp domain of expression and the position of the first constriction are shifted posteriorly in dpp\(^{shve}\) mutants (Fig. 3B). These effects are identical to the effects that Ubx mutations have on the positions of Antp expression and the first constriction, indicating that the morphological defects caused by dpp\(^{shve}\) mutations are a consequence of the greatly reduced expression of Ubx in PS 7. However, we also find that dpp expression in PS 7 is reduced or absent in Ubx mutant embryos (Reuter et al. 1990), therefore the lack of either sufficient Ubx or dpp gene product could be responsible for the shift in the Antp expression domain and the position of the first constriction.

Extracellular dpp protein moves from the visceral mesoderm across the endoderm

The similarity of dpp to the TGF-β family of growth factors (Padgett et al. 1986) and the fact that it is secreted from Drosophila cells in culture (Panganiban et al. 1990) led us to examine whether dpp might move from its sites of synthesis in the embryo. In the PS 7 region of the developing midgut, dpp RNA is detected in the visceral mesoderm cells at and anterior to the developing second constriction at stages 11-17 (Fig. 5A,SB, and data not shown) (stages according to Campos-Ortega and Hartenstein, 1985). Polyclonal antibodies to dpp (Panganiban et al. 1990) detect protein in and around these same visceral mesoderm cells at stage 14 (Fig. 5C). By stage 16, dpp protein is also detected surrounding the underlying endoderm cells (data not shown). By stage 17, most of the dpp protein is concentrated at the luminal surface of the endoderm cells (Fig. 5D), while the RNA can still be detected only in the mesoderm (Fig. 5B). This indicates that dpp protein, secreted from visceral mesoderm cells, moves from its site of synthesis across at least one cell layer. The fact that the site of synthesis is the visceral mesoderm and the adjacent cells are endoderm, raised the intriguing possibility that dpp might be involved in intercellular communication or inductive interactions between the two germ layers.

Absence of dpp in the visceral mesoderm eliminates lab expression in the endoderm

The homeotic gene lab is expressed in the endodermal cells between the first and second constrictions
Fig. 5. *dpp* RNA (A and B) versus protein (C and D) localization at and anterior to the second midgut constriction in 6 micron sagittal sections of stage 14 (A and C) and 17 (B and D) wild-type embryos photographed at 100×. While *dpp* RNA remains localized to the visceral mesoderm cells (vm), *dpp* protein migrates through the endoderm (ed) cells and by stage 17 is concentrated at the apical surface of the endoderm cells adjacent to the yolk (y).

(Diederich et al. 1989; and Fig. 6A), directly beneath the visceral mesoderm cells that express *Ubx* and *dpp*. Minor defects in second constriction formation have been reported to occur in *lab* mutants (Immergluck et al. 1990). In *dpp* mutant embryos, *lab* expression is absent from the endodermal cells of the midgut (Fig. 6B) indicating that the migration of the *dpp* protein from the mesoderm across the endoderm (Fig. 5) may induce the expression of *lab* in the underlying endoderm.

Mutations in *abdA* expand the domains of expression of *Ubx*, *dpp*, and *lab*

The *abdA* gene is expressed in the midgut visceral mesoderm in parasegments 8–12 (Tremml and Bienz, 1989a; Karch et al. 1990) and inhibits the expression of *Ubx* in the posterior midgut (Bienz and Tremml, 1988). Although wild-type expression of *Ubx* (Fig. 7A) and *dpp* (Fig. 7C) are limited to the PS 7 visceral mesoderm, their expression in an *abdA* mutant embryo is no longer restricted to PS 7, but extends over the entire posterior midgut (Fig. 7B,D). To determine whether the ectopic expression of *dpp* in the visceral mesoderm induces ectopic expression of *lab* in the adjacent endodermal cells, we examined the *lab* expression in *abdA* mutant embryos. In contrast to the wild-type pattern of *lab* expression (Fig. 7E), we find that the domain of *lab* expression is extended in the *abdA* mutants to include the endoderm of the posterior midgut directly beneath the visceral mesoderm cells that ectopically express *dpp* (Fig. 7F).

Discussion

Similarities in the expression patterns of *dpp* and *Ubx* in the visceral mesoderm led us to examine the regulatory relationships between *dpp* and homeotic genes during midgut development. We have identified three responses to *dpp* in the development of the *Drosophila* midgut that involve homeotic gene expression. The significance of these regulatory relationships to morphogenesis is best indicated by the fact that mutations in *dpp* alter the same structures, the gastric caeca and the second constriction, affected by mutations in two of the homeotic genes regulated by *dpp*. That *dpp* functions as a secreted factor is best illustrated by its regulation of a third homeotic gene across germlayers.

dpp regulation of Scr expression and gastric caeca formation

dpp negatively regulates Scr expression in the visceral
Fig. 7. Ubx, dpp and lab expression in abdA mutant embryos. Ubx (A), dpp (C), and lab (E) are normally expressed in the central region of the midgut. abdA is normally expressed in the visceral mesoderm cells of the posterior midgut (Karch et al.). In abdA<sup>AN</sup> mutant embryos, the domains of expression of both Ubx (B) and dpp (D) are expanded to include the visceral mesoderm cells in the posterior midgut (pm) as well. When dpp is ectopically expressed in the visceral mesoderm of the posterior region of the midgut due to a mutation in abdA, the expression of lab is activated in the endoderm cells of the posterior region of the midgut (F). Panels A–D are dorsal views photographed at 40×; E and F are lateral views photographed at 63×.

Mesoderm cells that become the caeca (Fig. 8). In dpp<sup>AN</sup> mutants, the domain of Scr expression at the gastric caeca is extended anteriorly to include those cells that normally express dpp. The ectopic expression of Scr in these cells may prevent the cells from evaginating as caeca. Alternatively, ectopic Scr expression by itself may not be sufficient to block development of the caeca but may serve as an indicator that the cell fate at the anterior end of the midgut is changed in the absence of dpp. The cell fate indicated by Scr expression must then be incompatible with the processes needed to form caeca. The mechanism by which dpp normally represses Scr expression in the anterior midgut and permits development of the caeca remains to be determined.

Although ectopic expression of Scr blocks the development of caeca, normal expression of Scr immediately posterior to the cells forming the caeca is required for caeca development (Reuter and Scott, 1990). As dpp expression at the anterior end of the midgut is not affected in the Scr mutant embryos, dpp expression, while required, is not sufficient for caeca development. The two adjacent regions of visceral mesoderm cells at the anterior end of the midgut, one
expressing dpp and the other expressing Scr, must cooperate to direct the formation of the gastric caeca.

dpp and Ubx regulate one another

Wild-type expression of both dpp and Ubx is crucial for development of the midgut (Fig. 8) because in the absence of either Ubx or dpp the second constriction does not form. These two genes positively regulate the expression of one another: in the absence of dpp function in the gut, Ubx expression is reduced, but not absent, and in the absence of Ubx function, dpp expression is reduced or absent depending on the Ubx allele (See Reuter et al. 1990 for discussion of the regulation of dpp expression by Ubx). This is in contrast to what has been reported by Immergluck et al. (1990) who report a unidirectional effect of Ubx on dpp. By analogy to the relationship between dpp and zen (Rushlow et al. 1987; Rushlow and Levine, 1990), we predict that Ubx is required for the initiation of dpp expression in PS 7, and that dpp is in turn required to maintain expression of Ubx. This prediction is consistent with the range of Ubx expression phenotypes we observe in dpp^{zen} mutant embryos.

The requirement for the coordinated activities of Ubx and dpp is illustrated by the posterior extension of Antp expression and the posterior shift of the first constriction in embryos mutant for either dpp or Ubx. As expression of both dpp and Ubx is regulated negatively by abdA (Fig. 7) it is of interest to determine whether abdA acts on both genes independently or whether, for example, the effects of abdA on Ubx expression are mediated by abdA's negative regulation of dpp expression. When both abdA and Ubx are expressed in the same cells, abdA can still repress dpp expression (Reuter et al. 1990) but it is not yet known whether abdA can also repress Ubx in the presence of ectopic dpp expression.

dpp migration across germ layers affects lab expression

One of the most interesting results of these experiments is that the dpp protein, after migrating from the visceral mesoderm across the endoderm, may induce the expression of the lab gene in the endoderm cells. In support of this mechanism, ectopic expression of dpp in the visceral mesoderm cells in abdA mutant embryos gives rise to a parallel ectopic expression of lab in the endoderm of the posterior midgut. Because Ubx and dpp are colocalized in the part of the visceral mesoderm of wild-type embryos that overlies the lab-expressing endoderm, and because Ubx is also ectopically expressed in the posterior midgut of abdA mutants, it remains a formal possibility that Ubx acts via a dpp-independent pathway to stimulate lab expression in the adjacent tissue. We believe this is unlikely because in dpp^{zen} mutants, which retain some Ubx expression, lab is not expressed in the underlying endoderm.

The fact that dpp is a secreted protein makes it a
strong candidate for regulation of gene expression between germlayers. However, the movement of dpp is quite limited. We do not observe extracellular dpp protein moving into regions of the visceral mesoderm that do not make dpp mRNA and cannot detect it migrating into or across the endoderm at the anterior end of the midgut. Perhaps dpp is associated with other extracellular proteins which limit its movement. We have observed that dpp protein produced in a Drosophila cell culture expression system associates with other proteins on the surface of the tissue culture dish (Panganiban et al., 1990). The Drosophila wingless gene product also appears to exhibit a limited potential for movement from the cells in which it is made (van den Heuvel et al., 1989). However, even the limited movement of extracellular dpp may allow it to exert an influence in a specific domain, for example, PS 7 of the visceral mesoderm, such that the intercellular communication mediated by dpp stabilizes a specific cell fate decision in that domain. This mechanism allows a population of cells to cooperate in maintaining the cell fate of the population.

dpp exerts pleiotropic effects on homeotic gene expression and midgut morphogenesis

The developmental origin or the environment of cells must determine how cells respond to dpp because, as reported here, at least three different homeotic genes can respond to the presence of dpp in the midgut. The only previous report of a change in gene expression due to dpp dealt with the failure to maintain zen expression in the amnioserosa of dpp null animals (Rushlow and Levine, 1990); interestingly, zen also encodes a homeo-domain containing protein (Rushlow et al., 1987). The differences in homeotic gene expression between the dpp-expressing regions of the midgut are paralleled by morphogenetic differences in these regions of the gut. In one dpp domain, the caeca are formed, while in the other a constriction is formed. Although dpp and Ubx are necessary to form the second constriction, they are not sufficient for constriction formation, as is illustrated by the absence of the second and third constrictions in abdA mutant embryos in which Ubx and dpp are expressed throughout the posterior midgut. Therefore, the effects of dpp on both gene expression and morphogenetic events are specific in different positions in the embryo. We propose that expression of dpp is necessary, but not sufficient, for specific aspects of homeotic gene expression and morphogenesis required to form the Drosophila midgut. The mechanisms by which the domains of dpp and homeotic gene expression are initially established in the visceral mesoderm remain to be determined. Clearly, once expressed, the genes regulate one another.

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