Myoblast determination in the somatic and visceral mesoderm depends on Notch signalling as well as on milliways (miliAlk) as receptor for Jeb signalling

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Summary

The visceral muscles of the Drosophila midgut consist of syncytia and arise by fusion of founder and fusion-competent myoblasts, as described for the somatic muscles. A single-step fusion results in the formation of binucleate circular midgut muscles, whereas a multiple-step fusion process produces the longitudinal muscles. A prerequisite for muscle fusion is the establishment of myoblast diversity in the mesoderm prior to the fusion process itself. We provide evidence for a role of Notch signalling during establishment of the different cell types in the visceral mesoderm, demonstrating that the basic mechanism underlying the segregation of somatic muscle founder cells is also conserved during visceral founder cell determination.

Searching for genes involved in the determination and differentiation of the different visceral cell types, we identified two independent mutations causing loss of visceral midgut muscles. In both of these mutants visceral muscle founder cells are missing and the visceral mesoderm consists of fusion-competent myoblasts only. Thus, no fusion occurs resulting in a complete disruption of visceral myogenesis. Subsequent characterisation of the mutations revealed that they are novel alleles of jelly belly (jeb) and the Drosophila Alk homologue named milliways (miliAlk). We show that the process of founder cell determination in the visceral mesoderm depends on Jeb signalling via the Milliways/Alk receptor.

Moreover, we demonstrate that in the somatic mesoderm determination of the opposite cell type, the fusion-competent myoblasts, also depends on Jeb and Alk, revealing different roles for Jeb signalling in specifying myoblast diversity. This novel mechanism uncovers a crosstalk between somatic and visceral mesoderm leading not only to the determination of different cell types but also maintains the separation of mesodermal tissues, the somatic and splanchnic mesoderm.

Key words: Drosophila, Myogenesis, Visceral and Somatic muscles, Founder cells, Fusion-competent cells, Myoblast fusion, Notch, Delta, lethal of scute, jelly belly, Alk, RTK signalling

Introduction

The early events of mesoderm formation and specification have been studied extensively (reviewed by Anderson, 1998), whereas the molecular mechanisms leading to different mesodermal cell types are less understood. The primordia of visceral, somatic and cardiac tissues are established at defined positions in each segment (Borkowski et al., 1995; Azpiazu et al., 1996; Riechmann et al., 1997; Hosono et al., 2003). The subdivision of mesodermal cells during gastrulation is the basis for the constitution of the main types of musculature in Drosophila: the somatic and visceral muscles. The formation of visceral midgut muscles depends on two homeobox genes, tinman (tin) and bagpipe (bap) (Bodmer, 1993; Azpiazu and Frasch, 1993). Expression of bap, which is required for the determination of the midgut visceral mesodermal anlage, is activated by Tin in the dorsal mesoderm. bap induction occurs in segmental clusters that migrate in anterioposterior direction forming a continuous band of visceral progenitor cells, which finally surrounds the midgut. Whereas bap is expressed transiently in the visceral precursor cells to determine the circular midgut muscles, the forkhead domain factor binou (bin) is activated downstream of bap and is necessary for the differentiation of all visceral derivatives. Hence, in bap and bin mutant embryos, the visceral mesoderm is partially transformed into somatic mesoderm (Azpiazu and Frasch, 1993; Zaffran et al., 2001).

Recently, Weiss et al. (Weiss et al., 2001) identified a novel signalling process that induces visceral cell identities. The jelly belly (jeb) gene encodes a secreted protein that is produced from somatic mesodermal cells and taken up by visceral cells. In jeb mutants, no visceral muscles develop due to a failure
of differentiation in the existing Bap-expressing visceral precursors. The emerging picture shows, on the one hand, visceral determination genes such as tin, bap and bin, which are responsible for subdividing the mesoderm into different tissues and, on the other hand, inductive signals like Jeb, which promote interactions between these tissues.

The differentiated visceral musculature of the Drosophila midgut consists of an inner layer of circular muscles and an outer layer of longitudinal muscles (Campos-Ortega and Hartenstein, 1997), the latter persisting throughout metamorphosis (Klapper, 2000). The founder cells of the longitudinal muscles have a distinct primordium at the posteriormost part of the mesoderm (Tepass and Hartenstein, 1994; Georgias et al., 1997; Kusch and Reuter, 1999), whereas the circular visceral founder cells and all fusion-competent myoblasts (fcms) for both visceral muscle types originate from the trunk mesoderm (Klapper et al., 2002). Recently, it has been shown that both types of visceral muscles are syncytial and arise by fusion of founders and fcms (Klapper et al., 2001; San Martin et al., 2001; Klapper et al., 2002). These two classes of myoblasts are closely associated in a band of visceral precursors, which express markers such as Fasciclin III (Patel et al., 1987) and are characterised by bin expression (Zaffran et al., 2001). The ventralmost row of these visceral myoblasts consists of dumbfounded/kin of irre (duf/kirre)-expressing founder cells with a characteristic columnar shape. The more dorsally located fcms are characterised as such by a more globular morphology and by expression of sticks and stones (sns). During stage 12, binucleate circular muscles are built via fusion of these founders and fcms. This fusion process is disturbed in myoblast city (mnc), duf/kirre and sns mutants, which are also known to be defective in somatic muscle fusion, indicating that the founder cell hypothesis applies both to somatic and visceral myogenesis. Thus, several of the known genetic components are common between somatic as well as visceral myoblast fusion (Klapper et al., 2001; San Martin et al., 2001; Klapper et al., 2002).

Differentiation of the syncytial somatic muscles depends on the determination of founder and fusion-competent myoblasts (Bate, 1990; Dohrmann et al., 1990). These two classes of myoblasts are specified by lateral inhibition by the neurogenic genes Notch and Delta from a group of equivalent somatic mesodermal cells (Carmena et al., 2002). As a consequence, expression of the proneural gene lethal of scute (lsc) is restricted to muscle progenitor cells. These progenitors divide asymmetrically and give rise to muscle founder cells (Carmena et al., 1995), which are characterised by differential expression of myogenic genes (reviewed by Baylies et al., 1998; Paululat et al., 1999). After establishment of myoblast diversity, the fusion process starts, leading in a first fusion step to muscle precursor cells and in a second fusion step to formation of mature myotubes (Dobestein et al., 1997; Rau et al., 2001). This process can be disturbed at distinct levels (reviewed by Dworak and Sink, 2002; Taylor, 2002). Besides lateral inhibition and determination through distinct transcription factors cell-cell signalling is an important mechanism in myogenesis.

Receptor tyrosine kinases (RTKs) are involved in intercellular communication in a wide range of processes. RTKs are composed of three domains: an extracellular ligand-binding domain, a single membrane-spanning domain and a cytoplasmic catalytic domain (Yarden and Ullrich, 1988). Ligand binding to the extracellular domain induces activation of the kinase on the cytoplasmic side, which initiates the intracellular signalling. The activated RTKs phosphorylate themselves and cytoplasmic substrates, leading to activation of a number of downstream signalling molecules, and ultimately induce changes in gene expression and the phenotypic state of the cell (Fangl et al., 1993; van der Geer et al., 1994). RTKs thus play important roles in cellular proliferation and differentiation. The role of RTKs during embryonic development and especially during the determination of distinct cell types has been studied in detail in Drosophila (reviewed by Rebay, 2002). During specification of muscle progenitor cells from equivalent cell clusters, the Ras/MAPK pathway functions as an inductive cellular determination signal. This pathway is activated by both epidermal and fibroblast growth factor receptors in the dorsal embryonic mesoderm [(Gabay et al., 1997); DER (Buff et al., 1998) and htl (Michelson et al., 1998)], while Notch antagonises this activity by lateral inhibition (Carmina et al., 2002). Recently, a novel RTK named DAlk (Drosophila Anaplastic Lymphoma Kinase; Alk – FlyBase) was described which is expressed specifically in the developing visceral mesoderm and CNS of Drosophila (Loren et al., 2001). Furthermore, activation of Alk mediated signalling is required for embryonic gut development and more specifically for the activation of MAP kinase in the visceral mesoderm (Loren et al., 2003). As Alk drives MAPK activation in the visceral mesoderm it is an obvious candidate to be involved in determination of distinct visceral cell types. In a search for genes involved in the determination of visceral cell types, we screened a collection of EMS-induced lethal mutations established previously (Hummel et al., 1999a; Hummel et al., 1999b) and identified two independent mutations with a nearly identical phenotype. Both exhibit a loss of circular visceral founder cells at early stages of visceral development, whereas fusion-competent visceral myoblasts are specified correctly and express markers like Fas3 and Sns. This results in a complete absence of visceral midgut muscles. Complementation analysis revealed that one mutation belongs to the previously described jelly belly (jeb) gene, while the second mutation named milliways (miiw) represents an Alk allele. We describe the crucial role of these genes in the process of visceral founder cell determination and analyse the role of Notch and Delta during the distinction between visceral cell types. Moreover, we uncover Jeb signalling via the Alk RTK as a new determination step for the fusion-competent cells of the somatic mesoderm.

**Materials and methods**

**Flystocks**

To find out whether Notch and Delta mutants have defects in founder cell determination in the visceral mesoderm, we used N5Se11 and DpB2 mutants from the Bloomington Drosophila Stock Center. For analysis of the involvement of Notch and Delta in the founder determination process we used a dominant-negative form of Notch [UAS-dnNotch (Rebay et al., 1993; Go et al., 1998)], UAS-Notch+Delta (Bloomington Drosophila Stock Center, M. Muskavitch, unpublished) and UAS-Notch1trans flies (Lieber et al., 1993). UAS-Notch1trans allows expression of a constitutive active form of the Notch receptor.

The collection of EMS mutagenised flies was obtained from Christian Klämbt (Hummel et al., 1999a; Hummel et al., 1999b). To
screen for mutants with defects in the determination of founder cells in the visceral mesoderm, we stained 180 lines on the second and 270 lines on the third chromosome, with anti-Fas 3 antibodies (Patel et al., 1987). We isolated a new jeb allele, jeb

and a new Alk allele, which we named mit

These two mutants were used for all experiments described herein.

For complementation tests we used jeb

(Nose et al., 1998; Klapper et al., 2002) and in the entire mesoderm using bap-lacZ (Azpiazu and Frasch, 1993; Zaffran et al., 2001). Overexpression studies were carried out using a bap-GAL4 driver line (Zaffran et al., 2001), which drives expression in the circular visceral mesoderm from stage 10 onwards or a twist-GAL4 driverline (SG24-GAL4), which drives expression in founder cells (gift from A. Michelson). As UAS lines we used UAS-Alk (Loren et al., 2001) and UAS-jeb flies (Weiss et al., 2001). All overexpression studies were carried out at 25°C.

Immunohistochemical staining

Immunostaining was performed as described previously (Knir et al., 1999; Klapper et al., 2002). The mouse Fas3 antisemur (Patel et al., 1987) was used for the visualisation of the visceral mesoderm cells (diluted 1:5, gift from C. Klämht). A rabbit anti-β-galactosidase antibody (Biotrend, diluted 1:2500) was used to visualise muscle founder cells in the enhancer trap line rP298-lacZ (Nose et al., 1998; Klapper et al., 2002) and the entire mesoderm using bap-lacZ (Azpiazu and Frasch, 1993; Zaffran et al., 2001). Overexpression studies were carried out using a Bap-GAL4 driver line (Zaffran et al., 2001), which drives expression in the entire mesoderm (gift from A. Michelson). As UAS lines we used UAS-Alk (Loren et al., 2001) and UAS-jeb flies (Weiss et al., 2001). All overexpression studies were carried out at 25°C.

In situ hybridisation

In order to visualise fcms in the mesoderm, whole-mount fluorescent DNA hybridisation was performed with random digoxigenin-labelled

and stones (sns) as a marker for these cells (Fig. 1D,E). This reduction is not as severe as in the somatic mesoderm but still quite obvious. In Delta mutants, the number of founder cells also seems to be increased in comparison with the wild type and the fcms are reduced in mutant embryos (Fig. 1C,F).

These observations cannot exclude the possibility that the observed phenotypes are induced by secondary effects from defects in other tissues, among others the lack of fcms in the somatic mesoderm. We therefore decided to perform overexpression studies using the UAS-GAL4 system (Brand and Perrimon, 1993). The GAL4 and UAS lines employed here also carry rP298-lacZ (Nose et al., 1998), which serves to mark the founder cells. As a driver line we used bap-GAL4 (Zaffran et al., 2001) to drive expression in the entire trunk visceral mesoderm. Expression of UAS-Notch + Delta, which contains the entire coding regions of both genes (M. Muskavitch, unpublished) or UAS-Notch

represents a constitutively active form of Notch (Lieber et al., 1993), in the visceral mesoderm, both result in a distinct phenotype. In midgut preparations of these embryos the founder cells of the circular visceral mesoderm are strongly reduced (Fig. 1K,L; data not shown for UAS-Notch+Delta) and later on, no functional visceral mesoderm can be observed (data not shown). By contrast, the founder cells of the longitudinal visceral muscles, which have a different origin at the posterior tip of the embryo are still present (arrowheads in Fig. 1K,L). Interestingly, bap-GAL4-driven expression of the Notch ligand Delta does not result in fewer founder cells in the visceral mesoderm (data not shown).

To exclude the possibility that the described defects are due to non-endogenous effects induced by the overexpression of the examined genes in the wrong tissue, we analysed wild-type Notch expression and found that it is indeed expressed in the visceral mesoderm. Notch is localised at cell membranes in the visceral mesoderm, both result in a distinct phenotype. In midgut preparations of these embryos the founder cells of the circular visceral mesoderm are strongly reduced (Fig. 1K,L; data not shown for UAS-Notch+Delta) and later on, no functional visceral mesoderm can be observed (data not shown). By contrast, the founder cells of the longitudinal visceral muscles, which have a different origin at the posterior tip of the embryo are still present (arrowheads in Fig. 1K,L). Interestingly, bap-GAL4-driven expression of the Notch ligand Delta does not result in fewer founder cells in the visceral mesoderm (data not shown).

To exclude the possibility that the described defects are due to non-endogenous effects induced by the overexpression of the examined genes in the wrong tissue, we analysed wild-type Notch expression and found that it is indeed expressed in the visceral mesoderm. Notch is localised at cell membranes in the entire visceral mesoderm during stage 11, with expression becoming weaker in the fcms of the visceral mesoderm, which continue to express bap-lacZ after the determination process is finished (Fig. 1G,H, arrowhead in G). This reduction of Notch expression in the fcms after the establishment of the founder cells is similar to its expression in the somatic mesoderm, where Notch expression is also highest in the progenitor cell after the determination process is completed (Carmona et al., 2002). Surprisingly, the analysis of Delta expression exhibits that this Notch ligand is not expressed in the visceral mesoderm during founder cell formation. Delta expression was found in adjacent, probably somatic cells (Fig. IIJ) and might be
Fig. 1. Notch signalling is involved in founder cell determination in the visceral mesoderm. The visceral mesoderm is visualised by Fas3 (red in A,B,C,M), β-galactosidase expression from bap-lacZ (red in H,J) and founder cells are marked by rP298-lacZ expression (green in A,C,M brown in K,L). (A) Visceral mesoderm (vm) of a stage 11 wild-type embryo. (B) In Fas3 staining of Notch^{5S5e11} embryos, it seems as if most cells of the vm are converted into founder cells as indicated by the stronger Fas3 expression and the more rectangular shape. (C) In stage 11 Delta^{B2} mutants, the number of founder cells also seems to be increased in the visceral mesoderm and fewer fcms are visible (compare C with A). The clusters of rP298-lacZ-positive cells ventral to the visceral mesoderm belong to the somatic mesoderm (sm). (D-F) sns in situ hybridisation comparing the wild type (D) where sns is expressed in two bands with the sns expression in N^{5S5e11} (E) and D^{B2} (F) embryos where it is reduced. This reduction is more severe in the ventral band of the fcms of the somatic mesoderm but also visible in the dorsal band of the fcms of the visceral mesoderm. (G,H) Notch expression in the visceral mesoderm in stage 11 embryos. (G) Notch is expressed ubiquitously at the membrane of all cells of the visceral mesoderm. (H) Some cells seem to have a lower expression level of Notch (arrowhead in G). These cells also express bap-lacZ, which at this stage is mainly restricted to the fcms (H). (I,J) In contrast to the N expression Delta is expressed in the cells adjacent to the bap-lacZ positive cell clusters of the visceral mesoderm. (K) rP298-lacZ expression in the gut of a stage 14 wild-type embryo. (L) In gut preparations of stage 14 embryos with ectopic expression of UAS-N^{intra} in the visceral mesoderm, the number of rP298-lacZ positive founder cells of the circular visceral musculature is decreased. Founder cells of the longitudinal visceral muscles are not affected and migrate normally in anterior direction (arrow in L). (M) In stage 11 embryos overexpressing a dominant-negative form of Notch (UAS-dnN) with a bap-GAL4 driverline, the number of rP298-lacZ positive founder cells is increased compared with the wild type (A) and also some cells which are not marked by lacZ expression exhibit a stronger Fas3 expression, which is characteristic for the founder cells in the visceral mesoderm.

needed there to participate in the visceral determination process, as indicated by the increased number of founder cells and reduced number of fcms in Delta mutants. Even though DI is expressed in the cells surrounding the visceral mesoderm, ectopic expression of UAS-DI in these cells with a twi-GAL4 driver line does not result in an obvious phenotype (data not shown), which might be due to the fact that the amount of Delta in this tissue is not the limiting factor that restricts Notch signalling. Another explanation for a missing Delta expression in the visceral mesoderm might be that a different factor acts as a ligand for Notch in the visceral mesoderm and that the observed phenotype in Delta mutants is due to secondary effects.

As the ectopic expression causes such a severe phenotype we also tested the lethality of these embryos (Fig. 2). Most of the progeny of the cross between the bap-GAL4 driver line and UAS-N^{DI} or UAS-N^{intra} develop and hatch but die as first larvae (78% or 70%), presumably owing to the fact that they cannot ingest any food. Ectopic expression of UAS-DI alone also increased lethality compared with the UAS and GAL4 lines alone (data not shown), but still ~65% of the larvae survive.

To confirm these results, we overexpressed a dominant-negative form of Notch [UAS-dnN (Rebay et al., 1993; Go et al., 1998)] specifically in the visceral mesoderm with a bap-GAL4 driverline. The embryos exhibit an obvious duplication of most visceral founder cells but still some fcms remain (Fig. 1M).

From these results, we conclude that Notch plays a role in the determination of the founder cells and fcms in the visceral mesoderm. Delta, which is expressed in the cells surrounding the visceral mesoderm, might serve as the ligand in this process but it is also possible that another factor takes over this role. Hence, not only is the fusion mechanism between the founder cells and the fcms in the somatic and visceral mesoderm conserved (San Martin et al., 2001; Klapper et al., 2002), but so is the initial mechanism of determination of these two cell types.

A screen for genes involved in visceral mesoderm development

To find out more about the mechanisms involved in the formation of the visceral muscles, we decided to screen a collection of EMS mutagenised flies (Hummel et al., 1999a; Hummel et al., 1999b) in order to search for genes involved in the determination of the two visceral cell types as well as in other aspects of visceral mesoderm differentiation.

Mutant embryos were stained and analysed with Fasciclin 3 (Fas3) (Patel et al., 1987), which marks the complete visceral mesoderm and allowed us to distinguish between the two cell types. Founder cells show a strong Fas3 expression and are characterised by a more columnar shape, while the more globular fcms show a clearly weaker Fas3 expression (Klapper et al., 2002). Using this approach, we identified several mutants with various defects in the development of the visceral musculature. These novel mutants can be summed up in four subgroups (Fig. 3).
The first group (G1) shows no Fas3 staining in the visceral mesoderm at any stage of embryonic development when compared with the wild type (Fig. 3A,D). In these G1 mutants, the initial subdivision of the mesoderm in precursors of the somatic and visceral mesoderm might be defective. The second group (G2) shows Fas3 staining in the visceral mesoderm, but the cells fail to form a continuous band (Fig. 3E) as is observed in wild type from stage 11 onwards (Fig. 3B). The third group (G3) shows defects at even later stages. Here, the continuous band of the visceral mesoderm forms, but the cells do not migrate dorsally or ventrally (Fig. 3F) and thus do not encircle the midgut as they do in wild-type embryos (arrowhead in Fig. 3C). It remains unclear whether this is due to a failure of myoblast fusion or to other reasons. The analysis of these mutants will be described elsewhere, while the fourth group (G4) is described here.

Identification of jelly belly (jeb) and the receptor for Jeb, milliways (mili) the Drosophila Alk homologue

In the same screen, we found a fourth subgroup (G4) consisting of two independent mutations, wellville (weli) and milliways (mili), with the same, distinct phenotype (Fig. 4). In these two mutants, the continuous band of the visceral mesoderm in stage 11 is formed, but when stained with Fas3, the more columnar shaped founder cells with the stronger Fas3 expression are absent (Fig. 4B,C compare with A). Thus, it appears that the founder cells of the circular visceral muscles are not determined in either of these mutants. Using the enhancer trap line rP298-lacZ, which shows a β-galactosidase pattern reflecting the expression of Duf/Kirre (Nose et al., 1998; Ruiz-Gómez et al., 2000), we could indeed show that in both mutants this founder cell marker is not expressed in the visceral mesoderm (Fig. 4E,F, compare with D). In contrast to these observations, the determination of founder cells in the somatic mesoderm is not affected (Fig. 4J-L), and the somatic muscle pattern shows only mild fusion defects, which are especially obvious in the dorsal and ventral muscles (Fig. 6A-C). At later stages no visceral mesoderm is present in either mutant (Fig. 4H,I, compare with G).

Both mutations, weli and mili, are located on the second chromosome. Complementation tests were subsequently performed with mutants on the second chromosome, which are known to affect visceral mesoderm development. Surprisingly, this analysis revealed that weli is a new jelly belly (jeb) allele. jeb encodes a secreted protein that is produced in the somatic mesoderm but is needed for proper visceral mesoderm formation and has been proposed to be essential for the migration and differentiation of the visceral mesoderm (Weiss et al., 2001). The phenotype of the specific loss of founder cells of the circular visceral muscles has not been described.

mili displays the same distinct phenotype as jeb and we reasoned that it is likely that both genes are involved in the same pathway. As Jeb is a secreted protein the most promising candidate for mili was Drosophila Alk, a member of the Alk/Ltk family of receptor tyrosine kinases (RTKs), which is expressed in the nervous system and the visceral mesoderm (Lorén et al., 2001). Alk is considered to be a possible receptor for jeb signalling (Lorén et al., 2003).

In order to further analyse whether mili is indeed an allele
founder cells in the visceral mesoderm by ectopic expression of UAS-Alk in the miliAlk mutant background using bap-GAL4 as driver (data not shown).

Thus, the two newly identified mutants, both of which display the same, very distinct, phenotype of loss of founder cells in the visceral mesoderm, turn out to be novel jelly belly and Alk alleles.

**The remaining cells of the visceral mesoderm in jebweli and miliAlk mutants differentiate to fusion-competent myoblasts**

We have shown that the cells of the visceral mesoderm in jebweli and miliAlk mutants do not express the founder cell marker rP298-lacZ and exhibit exclusively a globular shape upon Fas3 staining, which is characteristic for fcms. This raised the question of whether the cells indeed are determined to become fcms or remain undifferentiated. To clarify this question, we performed in situ hybridisation with sns as probe (Fig. 5). sns is expressed in all fcms, both in the somatic and in the visceral mesoderm (Bour et al., 2000; San Martin et al., 2001; Klapper et al., 2002). In the wild type during stage 11, two bands of sns-expressing cells can be observed in the mesoderm, which are connected in a ladder like pattern and represent the fcms of the somatic and visceral mesoderm (Fig. 5A). In jebweli and miliAlk mutants (Fig. 5B,C), only one band is present whereas the other band is missing. As indicated by the location of the connecting cells ventral of the present band, the dorsal band consisting of the fcms of the visceral mesoderm is still present (arrowheads in Fig. 5B,C). Thus, the remaining cells in the visceral mesoderm differentiate as fcms and express genes that are characteristic for this differentiated cell type.

**Jeb signalling and Alk expression are also responsible for fusion-competent myoblast differentiation in the somatic mesoderm**

The finding that in jebweli and miliAlk mutants in addition to the lack of founder cells in the visceral mesoderm also the fcms of the somatic mesoderm do not express fcm specific genes like sns was interesting as only mild defects in the somatic muscles are observed (Fig. 6B,C). To explain this phenotype, we took a closer look at the Alk expression in wild-type embryos. In addition to the expression of Alk in the cells of the visceral mesoderm, additional patches can be found in the neuroectoderm and the somatic mesoderm during stages 10 and 11 (Fig. 5D-F). We conclude that these patches of Alk expression in the somatic mesoderm are essential for the development of the somatic fcms because in Alk mutant embryos, which are unable to activate the RTK pathway, these cells do not express fcm-specific genes (Fig. 5C). Furthermore, jeb signalling is also required for this process, because the same phenotype can be observed in jeb

![Image](image_url)
mutants (Fig. 5B). Therefore the RTK signalling pathway involving Jeb and Alk is not only needed for founder cell specification of the visceral mesoderm but also for the differentiation of the fcms in the somatic mesoderm.

Having found that sns is no longer expressed in the fcms of the somatic mesoderm, we decided to look at the transcription factor lame duck/myoblast incompetent/gleeful (lmd/minc/glee), which is expressed in the somatic and visceral fcms and is responsible for their determination (Duan et al., 2001; Furlong et al., 2001; Ruiz-Gómez et al., 2002). The expression pattern of Lmd in the wild type is similar to that of sns and the protein is present in two bands in stage 11-12 (Fig. 5G). In both jebmutants and miliAlk mutants, the Lmd expression pattern is present (Fig. 5H,I) not only in the fcms of the visceral mesoderm but also in the somatic ones, even though it seems as if it is slightly weaker in the ventral part in the mutants than in the wild type. These data suggest that in jeb and mili mutants the initial determination of the fcms in the somatic mesoderm takes place, but the subsequent differentiation is blocked. Therefore, the Alk-RTK signalling pathway in the somatic mesoderm seems to be essential for the differentiation of the fcms but not for the initial determination.

The fusion-competent myoblasts of the visceral mesoderm become incorporated into the somatic mesoderm

Because most of the fcms of the somatic mesoderm are not expressing sns in jeb and mili mutants, we had a closer look at defects in this tissue. β-galactosidase antibody staining in mutants carrying the founder cell marker rP298-lacZ show a regular pattern of somatic founder cells compared with the wild type in the somatic mesoderm (Fig. 4J-L). Only in some of the mutant embryos could we detect local distortions because the defects in the visceral mesoderm (data not shown). β3tubulin antibody staining (Leiss et al., 1988) shows some mild fusion defects in the visceral mesoderm which normally is expressed exclusively in the visceral mesoderm throughout embryonic development (Azpiazu and Frasch, 1993; Zaffran et al., 2001) (Fig. 6D). We observe that jeb and mili

Fig. 5. The fusion-competent myoblasts of the somatic mesoderm do not differentiate in jeb and mili mutants. (A-C) sns in situ hybridisation of stage 11 embryos marks fcms in the visceral and somatic mesoderm. In wild-type embryos, sns is expressed in two bands along the entire length of the embryo (A). These bands are connected in a ladder-like pattern, where the ventral band represents the fcms of the somatic mesoderm (arrow in A), and the dorsal band consists of the fcms of the visceral mesoderm (arrowhead in A). In jeb (B) and mili (C) mutant embryos, the fcms of the visceral mesoderm and some cells that connect the two bands are present (arrowheads); however, the ventral band of fcms of the somatic mesoderm shows no sns expression. (D-F) Alk (green) and Fas3 expression (red) in stage 11 wild-type embryos. In addition to expression in the visceral mesoderm, Alk is also transiently expressed in some cells in the neuroectoderm and in patches in the somatic mesoderm (arrows in D,F). (G-I) Lmd expression of stage 12 embryos. In the wild type, Lmd is expressed in two bands in the fcms and visceral mesoderm (G). In jeb (H) and mili (I) mutants, expression in both mesodermal cell types can be observed.

Fig. 6. The cells of the visceral mesoderm of jeb and mili mutants become incorporated in the somatic musculature. Ventrolateral (A,B,C) muscles of stage 16 embryos as visualised by β3tubulin expression (green in A-F). Cells of the visceral mesoderm are marked by bap-lacZ expression (red in D-F). Compared with the wild type (A) the somatic muscles in both jeb and mili mutants are thinner and show long thin projections (B,C; arrow in B). Several unfused myoblasts are visible (arrow in C). (D-F) In wild-type embryos, no bap-lacZ expression is found in the somatic mesoderm during all stages of development (stage 14, D). By contrast, jeb and mili mutant embryos exhibit bap-lacZ expression in the lateral muscles of the somatic mesoderm (stage 14, E,F).
mutants carrying this marker show β-galactosidase expression in the somatic mesoderm from late stage 12 onwards (Fig. 6E,F).

From previous studies, it is known that a lack of sns expression in fcms in the somatic mesoderm results in strong defects in the somatic musculature where the founder cells become blocked at the point of myoblast fusion (Bour et al., 2000). Because we are not able to detect such a strong phenotype in miliAlk and Jebweli mutants, and together with the fact that bap-lacZ-expressing cells are present in the somatic mesoderm, we conclude that the sns-expressing cells from the visceral mesoderm now become incorporated into the somatic mesoderm and replace at least a fraction of the somatic fcms.

**Alk protein is mislocalised in miliwaysAlk mutant embryos and co-localises with Jeb at the membranes of visceral founder cells**

As *jeb* is a secreted protein we were interested whether the localisation of Alk controls the specification for the more ventral cells of the visceral mesoderm to become founder cells whereas the others develop into fcms. Staining with anti-Alk antibodies (Lorén et al., 2003) show that in the wild type the protein is localised at the cell membranes in the visceral mesoderm (Fig. 7A). Surprisingly, Alk can be found in the founder cells of the circular visceral muscles and in the fusion-competent myoblasts (Fig. 7A-C), which are not obviously affected in miliAlk mutants (Fig. 4C,F).

In Jebweli mutants, the localisation of Alk is not affected. Identical to the wild type, it localises at the cell membranes and is also present in all cells of the visceral mesoderm, which persist in these mutants (Fig. 7D-F). In miliAlk mutant embryos, however, the Alk protein is still detectable in all cells of the visceral mesoderm, but it is not correctly localised at the cell membrane and is instead found in the cytoplasm (Fig. 7G-I). Because of this mislocalisation and the fact that the embryos transheterozygous for *Df(2R)AlkA21* and miliAlk display the same phenotype in the visceral mesoderm as the miliAlk mutant embryos alone (data not shown), we conclude that the mutation is a phenotypic null allele even though at least the N-terminal part of the protein, against which the antibody is raised, is still present. As the Alk receptor is not properly localised, the founder cells cannot receive the Jeb signal and thus the signal transduction pathway leading to the activation of *duf/kirre* in the visceral founders is disturbed.

As Alk is localised at the membranes of all visceral cells and not only in the founder cells, we reasoned that the localisation of the Jeb protein must be responsible for the activation of the RTK pathway only in visceral founder cells. Therefore we postulate a co-localisation of both proteins only at the prospective founder cells. The double immunolabelling with Jeb (Weiss et al., 2001) and Alk (Loren et al., 2003) antibodies demonstrates that Jeb protein only co-localises at the membranes of the visceral founder cells with the Alk protein (Fig. 7J,K). Moreover, this specific interaction cannot be found in miliAlk mutants where, owing to the mislocalisation of the receptor protein, no Jeb uptake takes place (Fig. 7L,M). Therefore these mutants display an inactive RTK pathway.

**Ectopic expression of UAS-jeb results in an increased number of founder cells in the visceral mesoderm**

Previous work has shown that Jeb is secreted from the ventromedial cells of the somatic mesoderm, which are close to the visceral mesoderm (Weiss et al., 2001) (Fig. 9). Because all cells of the visceral mesoderm express the Alk RTK, it is theoretically possible that all are able to respond to *jeb* signalling. The fact that only the most ventral cells of the visceral
mesoderm display an active RTK pathway as a result of this interaction and later become the founders of the visceral mesoderm could be explained by the fact that these cells are closest to the cells that secrete the Jeb signal (Fig. 7K), which we suggest is the limiting factor. We therefore set out to test whether increased levels of Jeb can change the fate of the more dorsally located visceral fcms, which also express the receptor Alk, to become founder cells. We again used the UAS-GAL4 system and expressed UAS-jeb in the entire mesoderm with a twi-GAL4 driver. As expected, nearly all cells of the visceral mesoderm are now converted to founder cells (Fig. 8A,B). Even though fcms are missing, the founders are able to form visceral muscles that later on encircle the midgut. This ability to form muscles is one of the characteristics of founder cells. From sns and mbc mutants, it is known that even though no fusions take place, mini-muscles are formed in the somatic mesoderm that display the right orientation and attachment sites (Rushton et al., 1995; Bour et al., 2000). This has also been shown for the founder cells of the visceral mesoderm. In sns mutants, apart from the first gut constriction the visceral mesoderm develops normally (Bour et al., 2000). On closer inspection just the founder cells differentiate, whereas the fcms remain undifferentiated (Klapper et al., 2002). Thus, apart from the increased number of founder cells no defects are visible.

The same phenotype can be observed if UAS-jeb is ectopically expressed only in the visceral mesoderm (data not shown). sns in situ hybridisation confirms that through the overexpression of UAS-jeb in either the entire or just the visceral mesoderm, the fate of the fcms is changed so that they no longer express fcms-specific gene products such as SNS. This seems to be the reason why the band of fcms of the visceral mesoderm (Fig. 8D) is missing in these embryos (Fig. 8E). The somatic mesoderm (Fig. 8G) shows no defects as indicated by an anti-β3tubulin staining (Fig. 8H). Overexpression of UAS-jeb in a Alk mutant background shows that the UAS-jeb overexpression phenotype is suppressed in the Alk mutants (data not shown). Therefore jeb is dependent upon Alk as a receptor to activate the downstream signalling pathway.

In the wild type, the limited amount of the Jeb signal appears to restrict founder cell determination to the most ventral cells of the visceral mesoderm (Fig. 9). However, these findings prove that in principle all cells of the visceral mesoderm are able to respond to jeb signalling. Furthermore, we found no difference when the signal is produced from the somatic or the visceral mesoderm.

**Ectopic expression of UAS-Alk gives a similar phenotype as in miniAlk and jedweli mutants**

Anti-Alk stainings on embryos carrying the visceral mesoderm marker bap-lacZ show that Alk is expressed in all cells of the visceral mesoderm, some neuroectodermal cells and transiently in stage 10 to 11 in cell clusters in the somatic mesoderm (Fig. 5D-F, Fig. 9). We were interested in the consequences of ectopic expression of UAS-Alk in the entire mesoderm. Surprisingly, the overexpression of UAS-Alk by a twi-GAL4 driver produces a similar phenotype to
that in \textit{mili}^{Alk} or \textit{jeb}^{weak} mutant embryos. In early stage 11 only fcms are visible in Fas3 stainings (Fig. 8C) and later on there is no evidence of the presence of visceral mesoderm any more. In the somatic mesoderm, defects can be seen by an anti-\textit{\beta}3-tubulin antibody staining (Fig. 8I). Several muscles are small and display a spindle-like shape with long and thin projections, indicating that only few myoblasts fuse to form the muscles. In comparison with \textit{jeb}^{weak} and \textit{mili}^{Alk} mutants (Fig. 6B,C), in the Alk overexpressing embryos the muscle defects are stronger. Another surprising finding was that in this overexpression situation the \textit{sns}-expressing cells of the somatic mesoderm are again missing (Fig. 8F).

It remains an unanswered question why the overexpression of Alk in the entire mesoderm results in a similar phenotype to that in \textit{jeb}^{weak} and \textit{mili}^{Alk} mutants. One possible explanation for the visceral phenotype is that because of the absence of \textit{sns}-expressing cells in the somatic mesoderm, \textit{jeb} is not secreted anymore, which results in the absence of an active RTK pathway in the visceral founder cells. Therefore, we carried out anti-Jeb antibody stainings on these embryos. In stage 10 wild-type embryos, \textit{jeb} is expressed in two bands in the somatic mesoderm and disappears in stage 12 from all mesodermal derivatives (Weiss et al., 2001) (Fig. 8L). In embryos overexpressing Alk in the entire mesoderm, we could observe only one small group of \textit{jeb}-expressing cells per hemisegment (Fig. 8M). The reduced amount of the ligand Jeb thus phenocopies a \textit{jeb} mutant situation where the visceral founders are not determined.

A distinct difference between the founder cells and the fcms in the somatic mesoderm is the expression of \textit{lmd/\textit{minc}/\textit{glee}} in the fcms (Duan et al., 2001; Furlong et al., 2001; Ruiz-Gómez et al., 2002). We assume that in the wild type, only the fcms, which are characterised by this expression, are able to respond to the Jeb/Alk signalling pathway, which promotes the further differentiation of the somatic fcms. These in turn continue to secrete Jeb, which is required for the induction of the signalling pathway in the visceral mesoderm.

We assume that in the somatic mesoderm it is mainly the fcms that express Alk and suggest that the overexpression of Alk in the entire somatic mesoderm enables all cells of the mesoderm to take up the Jeb signal. Therefore, the signal necessary for the further differentiation of the fcms in the somatic mesoderm is downregulated through the increased Jeb uptake of the cells now ectopically expressing Alk. Another possibility to explain the visceral phenotype by overexpressing \textit{UAS-Alk} in the whole mesoderm is that the overexpression of Alk itself leads to a strong downregulation of Jeb. As a consequence, the visceral founder cells are not specified, again owing to the lack of Jeb signal.

A further indication for the relevance of these changes in the somatic mesoderm for the visceral phenotype arises from the overexpression of \textit{Alk} just in the visceral mesoderm with a \textit{bap-GAL4} driverline. This does not result in the phenotype described above. In this case, the founder cells in the visceral mesoderm are present and seem to be even increased in number (Fig. 8J-K). We assume that due to the Alk overexpression additional cells of the visceral mesoderm are now able to take up some of the limited amount of Jeb signal from the somatic mesoderm and thus become founder cells. In this case, Jeb expression in the somatic mesoderm is not affected.

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\textbf{Fig. 9.} The mode of action of Mili/Alk-mediated Jeb signalling during the determination and differentiation within the visceral and somatic mesoderm. At stage 10 (S 10) ventromedial somatic precursor cells start to express \textit{jelly belly} (\textit{jeb}, red cells) and secrete Jeb protein (small red dots) (Weiss et al., 2001). Some of these cells (red with green crescents) also express \textit{mili}^{Alk} (green) and all visceral precursor cells express \textit{mili}^{Alk} and \textit{bagpipe} (\textit{bap}) at this time. We conclude that Jeb signalling, especially the RTK pathway activation in visceral founder cells, depends on the level of Jeb protein reaching these cells. This activation leads in stage 11 (S 11) in the visceral mesoderm (vm) to the expression of \textit{dumbfounded}/\textit{kin of irre} (\textit{duf/kirre}, blue) in the visceral founder cells (f), whereas the fusion-competent myoblasts (fcms) without an active pathway are characterised by \textit{sticks and stones} (\textit{sns}) expression. We further suggest that initial \textit{jeb} expression in the somatic mesoderm (sm) is maintained mainly in \textit{lame duck}/myoblast incompetent/gleeful (\textit{lmd/\textit{minc}/\textit{glee}})-expressing fcms responding on RTK pathway activation with differentiation into \textit{sns}-expressing fcms. Nothing is known so far about the role of Jeb and Mili/Alk signalling in the ectoderm (ecto) and fat body (fb).
References


