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 syncytiot 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 mesoderms leading not only to the determination of different cell types but also maintaining 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 binou expression (Zaffran et al., 2001). The ventromost row of these visceral myoblasts consists of dumbfounded/bin 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), dufkirre 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 (Doberstein 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 (Faintl 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 (Carmena 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 (Lorén 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 (Lorén 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 (miliW) 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 N^{Se1/2} and D^{B2} 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-Notch^{prua} flies (Lieber et al., 1993). UAS-Notch^{prua} 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 (Pate et al., 1987). We isolated a new jed allele, jedk05644 and a new Alk allele, which we named mit216. These two mutants were used for all experiments described herein.

For complementation tests we used jedk05644 (Weiss et al., 2001) from the Bloomington Drosophila Stock Center, and Df(2R)Alk21 which is a deficiency covering 53C (Lorén et al., 2003). β-galactosidase-expression in founder cells was achieved using the enhancer trap line rP298-lacZ (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 driver line (SG24-GAL4), which drives expression in the entire mesoderm (gift from A. Michelson). As UAS lines we used UAS-Alk (Lorén 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 antisera (Pate et al., 1987) was used for the visualisation of the visceral mesoderm cells (diluted 1:5, gift from C. Klämbt). A rabbit anti-β-galactosidase antibody (Biotrend, diluted 1:2500) was used to visualise muscle founder cells in the enhancer trap line rP298-lacZ and a mouse anti-β-galactosidase antibody (Promega, diluted 1:500) was used to visualise bap-lacZ expression. For analysis of the somatic mesoderm, we used rabbit anti-β-tubulin antibodies at a dilution of 1:2500 (Leiss et al., 1988). The rabbit anti-Alk (diluted 1:500) (Lorén et al., 2003), rabbit anti-Jeb (diluted 1:100) (Weiss et al., 2001), rabbit anti-Lmd (diluted 1:1000) (Duan et al., 2001), mouse anti-Notch (diluted 1:10) (Fuß and Hoch, 2002) and mouse anti-Delta antisera (diluted 1:50, Developmental Studies Hybridoma Bank) were used in combination with the TSA signal amplification kit (NEN). For secondary antibodies, we used Cy2- and Cy3-labelled antibodies made in goat against rabbit and mouse from Dianova (diluted 1:40 and 1:100). The embryos were embedded in Fluormount G (Southern Biotechnology Associates) and photos were taken under Nomarski optics with a Zeiss Axiophot microscope or a Leitz confocal microscope and processed with Adobe Photoshop 6.0 (Adobe Systems).

In situ hybridisation
In order to visualise fcms in the mesoderm, whole-mount fluorescent DNA hybridisation was performed with random digoxigenin-labelled sticks and stones cDNA probes according to Knir et al. (Knir et al., 1999). The sns cDNA was a gift from S. Abmayr (Bour et al., 2000). For the combination with antibody stainings to visualise β-galactosidase expression we used anti-β-galactosidase antiserum (Cappel) at a dilution of 1:3000.

Lethal phase analysis
To test the lethality of the progeny from UAS-GAL4 crosses we mated homozygous lines carrying the founder cell marker rP298-lacZ, collected eggs for 24 hours and allowed further development for another 48 hours at 25°C. Afterwards, we counted at least 1000 progeny of each cross.

Results and discussion
Founder cell determination in the visceral mesoderm depends upon Notch
The process of lateral inhibition involving Notch and its ligand Delta, which was first discovered in the nervous system, also plays a role in determining the founder and fusion-competent myoblasts (fcms) of the somatic musculature (Carmena et al., 2002). As many of the processes involved in the development of the somatic musculature also seem to affect the development of the visceral muscles, we investigated whether the mechanism of determination of founder and fcms is also conserved.

Notch and Delta play important roles in various developmental processes and mutations in either gene lead to strong developmental defects during embryogenesis. Thus, it is difficult to analyse whether the visible defects in the visceral mesoderm are due to defects in the determination of the founder cells or are a result of secondary effects. In Notch mutant embryos more founder cells appear to be present in the visceral mesoderm (Fig. 1A,B). The visceral fcms seem to be reduced compared with the wild-type expression of sticks 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-NotchDelta, which 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-NotchDelta) 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 (Carmena 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. 1I,J) and might be...
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-dN or UAS-N\textsuperscript{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., 1998) specifically in the visceral mesoderm and that the observed phenotype in Delta mutants is due to secondary effects.

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Myoblast determination depends on N and Alk

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...
We then tested a newly created deficiency in the region (Df(2R)Alk\textsuperscript{21}) in which \textit{Drosophila} Alk has been removed (Lorén et al., 2003). Indeed, \textit{mili} is allelic to \textit{Df(2R)Alk}\textsuperscript{21}, and furthermore, embryos transheterozygous for \textit{Df(2R)Alk}\textsuperscript{21} and \textit{mili} show the same phenotype as \textit{mili} mutant embryos on Fas3 analysis (data not shown). We then tested \textit{mili} directly against the newly generated \textit{Alk}\textsuperscript{1} allele (Lorén et al., 2003) and could indeed confirm that \textit{mili} is a new \textit{Alk} allele, which we now named \textit{miliAlk}. The analysis of \textit{miliAlk} mutants with the help of Alk antibodies (Lorén et al., 2001) reveals that the mutant Alk protein is found in the cytoplasm instead of its normal localisation at the cell membrane. Therefore we conclude that the mutation is a phenotypic null allele. Furthermore, we could rescue the specific loss of founder cells in the visceral mesoderm by ectopic expression of \textit{UAS-Alk} in the \textit{miliAlk} mutant background using \textit{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 \textit{jelly belly} and \textit{Alk} alleles.

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

We have shown that the cells of the visceral mesoderm in \textit{jebweli} and \textit{miliAlk} mutants do not express the founder cell marker \textit{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 \textit{sns} as probe (Fig. 5). \textit{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 \textit{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 \textit{jebweli} and \textit{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 \textit{jebweli} and \textit{miliAlk} mutants in addition to the lack of founder cells in the visceral mesoderm also the fcms of the somatic mesoderm do not express fcms specific genes like \textit{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 fcms-specific genes (Fig. 5C). Furthermore, \textit{jeb} signalling is also required for this process, because the same phenotype can be observed in \textit{jeb}.
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 jeb\textit{weli} and mili\textit{Alk} 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\textit{weli} and mili\textit{Alk} 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\textit{weli} and mili\textit{Alk} mutants, we had a closer look at defects in this tissue. β-galactosidase antibody staining in mutants carrying the founder cell marker \textit{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 dorsal and ventral muscles in jeb\textit{weli} and mili\textit{Alk} mutants indicated by unfused myoblasts in this region and long thin projections of the muscles (Fig. 6B,C, compare with A).

The development of the visceral mesodermal cells cannot be followed with Fas3 staining because it disappears in the mutants after stage 11. Therefore, we visualised the fate of the fcms using the visceral mesoderm marker \textit{bap}-lacZ, 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\textit{weli} and mili\textit{Alk}
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 jeb weli 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 miliways Alk 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 jeb weli 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 are transheterozygous for Df(2R)Alk21 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 fcmspecific 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 miliAlk and jebweli 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 mili\textsuperscript{Alk} or jeb\textsuperscript{weel} 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-$\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 jeb\textsuperscript{weel} and mili\textsuperscript{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 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 jeb\textsuperscript{weel} and mili\textsuperscript{Alk} mutants. One possible explanation for the visceral phenotype is that because of the absence of sns-expressing cells in the somatic mesoderm, 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, 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 jeb-expressing cells per hemisegment (Fig. 8M). The reduced amount of the ligand Jeb thus phenocopies a 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 lmd/minc/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 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 Alk just in the visceral mesoderm with a 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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References


