The zinc finger proteins Pannier and GATA4 function as cardiogenic factors in Drosophila

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INTRODUCTION

The Drosophila heart is a linear organ that pumps haemolymph throughout the animal in an open circulatory system. During embryogenesis, bilateral groups of heart progenitor cells are produced within the dorsal mesoderm and these cells migrate to the midline where they fuse to form the heart tube (Lawrence et al., 1995; Azpiazu et al., 1996; Jagla et al., 1997; Gajewski et al., 1998). The dorsal vessel is composed of inner contractile cardial cells that are flanked by non-contracting pericardial cells. The central muscle cells express the differentiation factor D-MEF2 that activates the transcription of various structural protein genes, facilitating the contractile nature of the heart (Bour et al., 1995; Lilly et al., 1995; Ranganayakulu et al., 1995).

The specification of cardiac progenitors within the dorsal mesoderm requires the coordinated activities of several regulatory genes. The homeobox gene tinman (tin) plays an essential role in the patterning of the early mesoderm and multiple muscle defects are observed in tin mutant embryos (Azpiazu and Frasch, 1993; Bodmer, 1993; Gajewski et al., 1997, 1998; Yin and Frasch, 1998). These include an absence of heart precursor cells and a resulting lack of dorsal vessel formation. tin expression in the dorsal mesoderm is under the inductive control of Decapentaplegic (Dpp), a TGFβ-related signaling molecule produced by dorsal ectodermal cells (Frasch, 1995; Xu et al., 1998). Due to the deficiency of tin expression in dpp mutant embryos, cardiac mesoderm fails to develop. A second secreted molecule, Wingless (Wg), also plays a vital role in heart formation. By an unknown mechanism, Wg functions as a required co-regulator with Tin in the specification of heart precursor cells (Lawrence et al., 1995; Wu et al., 1995; Park et al., 1996; Jagla et al., 1997; Gajewski et al., 1998). Accordingly, the heart fails to form in wg mutant embryos. Another gene needed indirectly for the production of cardiac progenitors is heartless (htl), which encodes a fibroblast growth factor receptor homologue (Shishido et al., 1993). Htl functions in the directional migration of the invaginated mesoderm along the overlying ectoderm (Beiman et al., 1996; Gisselbrecht et al., 1996; Shishido et al., 1997). In mutant embryos, mesodermal cells do not migrate dorsally into the Dpp signaling domain, tin expression is not maintained and there is a failure of cardiac mesoderm development.

The earliest events of vertebrate heart development are remarkably similar to those observed in Drosophila as bilaterally symmetric heart progenitors are specified within the anterior lateral plate mesoderm and these cells migrate to the ventral midline where they form a linear beating heart tube (Bodmer, 1995; Olson and Srivastava, 1996). Inductive processes are also utilized in the specification of vertebrate cardiac precursors as signaling factors of the bone morphogenetic protein class,
related to *Drosophila* Dpp, are produced by the endoderm and interpreted by the precardiac mesoderm (Schultheiss et al., 1997). Thereafter, vertebrate-specific morphogenetic events occur such as looping of the linear tube and remodeling of the heart into a multichambered organ. The requirement of *tin* function for cardiogenesis in flies, coupled with the embryological similarities of heart formation between invertebrates and vertebrates, prompted a search for *tin*-related genes in other species. This led to the

![Fig. 1.](image1) **Fig. 1.** *pnr* is expressed in the cardiogenic mesoderm. (A) Lateral view of a late stage 10 embryo showing the broad domain of *tin* expression in the dorsal mesoderm. (B) Lateral view of a stage 11 embryo stained for *lacZ* expression under the control of the *D-mef2* heart enhancer. (C) Lateral view of a late stage 10 embryo showing *pnr* expression in the dorsal ectoderm. (D) Cross-section of a late stage 10 embryo showing *pnr* RNA in both the dorsal ectoderm and cardiogenic mesoderm. (E) Cross-section of a late stage 10 embryo showing *pnr* enhancer activity in the cardiogenic mesoderm and amnioserosa. (F) Lateral and (G) ventral views of a late stage 10 embryo demonstrating *pnr* enhancer function in the amnioserosa and dorsal mesoderm. The arrowhead points to the absence of *lacZ* expression in the dorsal ectoderm. Abbreviations: as, amnioserosa; cm, cardiogenic mesoderm; de, dorsal ectoderm; dm, dorsal mesoderm; hp, heart precursors.

![Fig. 2.](image2) **Fig. 2.** *pnr* functions during *Drosophila* cardiogenesis. (A-D) Activity of a *D-mef2* heart enhancer is greatly diminished in *pnr* mutant embryos. Early stage 12 embryos stained for *lacZ* expression under the control of a *D-mef2* combinatorial enhancer are shown. (A, C) WT, wild-type embryos. (B, D) *pnr* mutant embryos. (A, B) The focus is on the dorsal mesoderm to illustrate the presence or decrease (open arrow) in reporter gene expression. (C, D) The focus is on the ventral mesoderm to highlight normal *lacZ* expression in ventral muscle founder cells (filled arrow) of both embryo types. (E-H) *pnr* controls cardial and Eve pericardial cell specification. Wild-type (E, G) and *pnr* mutant (F, H) embryos were stained for D-MEF2 protein as a marker for cardial cells (E, F) or Eve protein as a marker for pericardial cells (G, H). In the wild-type embryo, the filled arrow points to a row of cardial cells. In *pnr* mutants, the open arrow indicates the absence of cardial cells while the filled arrow points to the excess number of Eve-expressing pericardial cells.
The discovery of numerous NK-2 class homeobox genes and several of the homologues are expressed in the cardiac lineage (Harvey, 1996). Recent genetic studies have demonstrated the importance of tin-related genes for vertebrate heart development, specifically in the mouse and *Xenopus* systems (Lyons et al., 1995; Grow and Krieg, 1998; Fu et al., 1998). The GATA4, GATA5, and GATA6 zinc finger transcription factors are also expressed in the forming vertebrate heart (Arceci et al., 1993; Kelley et al., 1993; Heikinheimo et al., 1994; Laverriere et al., 1994; Jiang and Evans, 1996; Morrissey et al., 1996, 1997; Jiang et al., 1998). The importance of GATA4 in heart development has been suggested based on its expression in the precardiac mesoderm, its presence in the differentiated myocardium throughout embryogenesis and into adulthood, and its regulation of multiple cardiac structural genes in cell culture studies (Grepin et al., 1994; Ip et al., 1994; Molkentin et al., 1994; Durocher et al., 1997; Lee et al., 1998; Sepulveda et al., 1998). However, genetic studies thus far have not demonstrated a definitive role for any GATA gene in cardiomyocyte specification (Kuo et al., 1997; Molkentin et al., 1997; Jiang et al., 1998; Morrisey et al., 1998; Morrisey et al., 1998; Koutsourakis et al., 1999).

The involvement of a GATA factor in *Drosophila* heart development has been hinted at based on the analysis of a cardinal cell enhancer of the *D-mef2* gene. This regulatory DNA is a direct target of Tin as it contains two required factor binding sites and ectopic Tin expression results in enhancer activity outside of the cardiac lineage (Gajewski et al., 1997). It has also been demonstrated that the two Tin sites alone are not sufficient and a GATA sequence element must be present in the enhancer for its normal function. Strikingly, mutation of this GATA element changes the transcriptional specificity of the enhancer from cardinal to pericardial cells (Gajewski et al., 1998). This result led to the hypothesis that Tin and a GATA site-binding protein(s) selectively activate or repress *D-mef2* expression in cells of the dorsal vessel. While three GATA genes, *pannier* (*pnr*), *serpent* (*srp*), and *dGATAc*, have been identified in *Drosophila*, their functions have been verified only in non-cardiac cells and their expression has not been reported in the heart lineage (Abel et al., 1993; Ramain et al., 1993; Winick et al., 1993; Lin et al., 1995; Heitzler et al., 1996; Rehorn et al., 1996; Sam et al., 1996; Riechmann et al., 1998). Thus, a combinatorial function of Tin and GATA transcription factors during *Drosophila* heart development represents a plausible but untested genetic paradigm.

In this report, we demonstrate that *pnr* is expressed in, and functions during, heart development in...
Drosophila, pnr acts as a cardiac cell identity gene and works synergistically with tin in the specification of the cardiac cell fate. Likewise, the homologous GATA4 protein of mice can serve as a cardiogenic factor in Drosophila. These results demonstrate a combinatorial activity of Tin and GATA proteins during heart development and identify a conserved function for two GATA factors in cardiac cell specification and gene regulation.

MATERIALS AND METHODS

Fly strains

y w^{67C23} served as our wild-type stock. The Ga4 strain used to direct gene expression in the mesoderm and mesectoderm was twi-Ga4 (Baylies and Bate, 1996). The UAS lines included UAS-pnr (Haenlin et al., 1997), UAS-tin (Yin and Frasch, 1998) and UAS-GATA4 generated in this study. The latter was obtained by isolating a 1.7 kb mouse GATA4 cDNA, containing the complete protein open reading frame, from the pMT2-GA4 TTA4 expression vector (Arceci et al., 1993) and cloning it into the EcoRI site of pUAST (Brand and Perrimon, 1993). Insert orientation and integrity were confirmed by DNA sequencing. The pUAST-GATA4 DNA was injected into y w^{67C23} embryos and 11 transgenic lines were established using standard transformation procedures as described in Gajewski et al. (1997). Ten of these showed moderate to strong function when tested in the fly cardiogenic assays. The pnr mutant strain used was pnr^{rl} ru st e ca/TM3; Sb, ftz-lacZ which was generated and designated P11. Expression of the D-mef2-lacZ gene was assayed in embryos of the following genotypes: P11/+;UAS-tin/+;UAS-pnr/+.

RNA in situ hybridization and embryo sectioning

A pnr cDNA cloned in pNB40 (Winick et al., 1993) was excised and inserted into pBluescript (Stratagene, La Jolla, CA). tin (NK4) and bap (NK3) cDNAs (Kim and Nirenberg, 1989) were also cloned into the same plasmid and linearized DNAs served as templates to generate antisense cRNA probes using the DIG RNA labeling kit (Roche, Mannheim, Germany). RNA expression in whole-mount embryos was detected using the protocol of Ingham and Jowett (1997), except that the prehybridization and hybridization steps were at 60°C. To investigate pnr expression in the mesoderm, stained embryos were postfixed for 5 minutes in 2% formaldehyde, rinsed in PBT and taken through a series of sucrose/PBS treatments (10%, 15%, 20%, 25%, 30% sucrose). Embryos were then saturated for 2 hours in a 1:1 mixture of 30% sucrose in PBS/Tissue-Tek OCT compound (VWR, West Chester, PA), transferred to a plastic OCT block and frozen on dry ice. 12 µm sections were obtained using a Reichert-Jung 2800 Frigocut Cryosectioner. Embryo sections or whole-mount embryos were mounted in 50% glycerol under coverslips for photography using a Zeiss Axioplan photomicroscope and Kodak Ektachrome 64T film.

Immunohistochemical staining of embryos

Embryos obtained from the mating of twi-Ga4 and the various UAS lines were collected at 29°C, while all other embryos were collected at 23°C. Processing and immunostaining of whole-mount embryos was as described in Patel et al. (1987) using the Vectastain Elite ABC Kit (Vector, Burlingame, CA). Primary antibody dilutions were as follows: mouse anti-β-galactosidase (Promega, Madison, WI), 1:1000; rabbit anti-D-MEF2 (Lilly et al., 1995), 1:1000; mouse anti-Eve (Developmental Studies Hybridoma Bank, University of Iowa), 1:100; mouse mAb3 (Yarnitzky and Volk, 1995), 1:50; mouse anti-Fascinillin III (Developmental Studies Hybridoma Bank), 1:50; rat anti-Sim (Nambu et al., 1990), 1:200. Biotin-conjugated secondary antibodies (Vector) were as follows: horse anti-mouse, 3:1000; goat anti-rabbit, 1:1000; rabbit anti-rat, 1:300. Immunostained embryos were photographed as described for RNA processed embryos.

To quantitate the relative numbers of cardiac cells present in wild-type, twi-Gal4;UAS-pnr and twi-Gal4;UAS-GATA4 embryos, D-MEF2-positive nuclei present within the dorsal vessel were counted in 20 embryos of the specific genotype. Similarly, the relative numbers of the Eve-expressing cells in wild-type versus twi-Gal4;UAS-pnr embryos were determined from counts of Eve-positive nuclei present in the dorsal mesoderm of 20 embryos of the two genotypes.

Gene expression analyses in mutant and Ga4/UAS embryos

To analyze the function of the D-mef2 heart enhancer in pnr mutant embryos, the IIA341 D-mef2 enhancer-lacZ fusion gene (integrated on chromosome III) was recombined onto the pnr^{rl} chromosome and a stock of the genotype y w; IIA341 pnr^{rl}/TM3, Sb, fzt-lacZ was generated and designated P11. Expression of the D-mef2-lacZ gene was assayed in pnr homozygous and heterozygous embryos, with the latter identified based on the expression of the marker linked to the balancer chromosome. Identical results were obtained when the P11 flies were out-crossed to wild-type flies, followed by mating of F_{1} w^{+} Sb^{+} siblings and staining of embryos for β-galactosidase activity. Likewise, the expression of the cardinal and pericardial cell markers were analyzed in embryos produced from matings of pnr^{rl}/TM3 or P11/+ flies, with comparable results obtained in either of the genetic backgrounds.

To analyze mesodermal and neural markers in embryos with forced expression of pnr, mGATA4 and/or tin, protein or RNA expression was assayed in embryos of the following genotypes: twi-Gal4;UAS-pnr and twi-Gal4;UAS-GATA4 obtained from crosses of homozygous twi-Gal4 females to homozygous UAS-pnr or UAS-GATA4 males and twi-Gal4;UAS-pnr/IIA341 and twi-Gal4/UAS-GATA4/IIA341, obtained from crosses of homozygous twi-Gal4;IIA341 females to homozygous UAS-pnr or UAS-GATA4 males. For the analysis of the IIA237 cardiac cell-specific enhancer, D-MEF2 protein and Sim protein in the mesodectoderm, twi-Gal4;IIA237 homozygous females were mated to UAS-pnr, UAS-GATA4 or UAS-tin homozygous males and UAS-tin/++;UAS-pnr/+ or UAS-GATA4/+; UAS-tin/+ transheterozygous males.

RESULTS

pnr gene expression and function in the cardiac lineage

pnr gene function is required for heart development in Drosophila (Azpiazu and Frasch, 1993; Bodmer, 1993). The initial programming of the cardiac lineage occurs at a time when tin is broadly expressed in the dorsal mesoderm (Fig. 1A). A subset of the tin-expressing cells will become heart precursors, appearing in 11 clusters along the dorso-lateral part of the mesoderm (Fig. 1B). The D-mef2 enhancer-lacZ fusion gene marks heart progenitors at stage 11 and will eventually be expressed in four pairs of cardiac cells per segment of the dorsal vessel (Gajewski et al., 1997, 1998; Nguyen and Xu, 1998). Thus, the tin expression domain is significantly larger than the territory of heart precursor specification, suggesting the involvement of additional factors in the formation of these cells.

The D-mef2 heart enhancer requires the presence of at least
three elements for its activity, including two Tin binding sites and one GATA sequence (Gajewski et al., 1997, 1998). It was previously shown that the GATA gene pnr is expressed in cells of the dorsal ectoderm around the time of heart cell specification (Winick et al., 1993; Heitzler et al., 1996; Fig. 1C). However, there was no report of pnr transcription in the mesoderm. To investigate this possibility, we stained embryos for pnr RNA and examined embryo cross-sections. At late stage 10, gene expression is observed in the dorsal ectoderm of the germband-extended embryo (Fig. 1D). We also detected pnr RNA in four clusters of cells located in the dorsalmost part of the mesoderm that corresponds to the cardiogenic region. Additionally, we identified a pnr mesodermal enhancer that directs lacZ expression in the heart-forming region, but not in the overlying ectoderm (Fig. 1E-G). Therefore, pnr is expressed in the cardiogenic mesoderm where it could function in cardiac cell specification and the regulation of D-mef2 transcription.

The D-mef2 IIA341 enhancer is active in both cardiac and ventral muscle founder cells (Fig. 2A,C) and a GATA site is needed for the cardiac cell expression (Gajewski et al., 1998). To determine if pnr function is important for enhancer activity in either of these cell types, we monitored the expression of the enhancer-lacZ fusion in pnr mutant embryos. We observed a strong reduction of reporter gene expression in the dorsal mesoderm of the mutants (Fig. 2B), while normal lacZ expression was detected in the ventral muscle precursors (Fig. 2D). These results suggest Pnr is a transcriptional regulator of the D-mef2 heart enhancer, consistent with the observation that the protein can bind the essential GATA sequence in an electrophoretic mobility shift assay (data not shown). Alternatively, or in addition, these results could be indicative of a requirement of pnr function for the formation of the D-mef2-expressing cardiac cells.

To determine if pnr function was essential for the specificiation of cardiac cells, wild-type and mutant embryos were stained for D-MEF2 protein that serves as a marker for these cells. A distinct row of cardiac cells is observed in a lateral view of normal embryos at stage 13 as they migrate dorsally along the overlying ectoderm during the process of dorsal vessel formation (Fig. 2E). In contrast, these cells are greatly diminished or completely absent from the dorsal mesoderm of mutant embryos (Fig. 2F). To assess the formation of the pericardial cells in the same genetic background, embryos were stained for Eve protein, which is a marker for a subset of these cells. Eleven clusters of Eve-positive cells, each comprising three or four cells, are detected in wild-type embryos at stage 12 (Fig. 2G). In contrast, an overabundance of Eve-expressing pericardial cells is observed in the pnr embryos (Fig. 2H). These results suggest that pnr function is vital to the formation of cardiac cells, while simultaneously playing an important role in controlling the production of at least one pericardial cell type.

**Forced expression of pnr results in supernumerary cardial cells**

To test the possibility that Pnr is an activator of the D-mef2 heart enhancer, we used the Gal4/UAS system (Brand and Perrimon, 1993) to force the expression of the GATA factor throughout the mesoderm, while monitoring the activity of the lacZ reporter gene under the control of the regulatory sequence. The driver line used was twi-Gal4, which directs Gal4 expression in the mesoderm throughout embryogenesis (Baylies and Bate, 1996). As noted, the enhancer is active in 11 clusters of heart precursor cells in wild-type embryos by stage 11 (Fig. 3A). In comparably staged embryos expressing pnr throughout the mesoderm, we observed a strong overactivation of the fusion gene in the dorsal mesoderm with both the intensity and cellular realm of β-galactosidase activity increased (Fig. 3B). In normal embryos at stage 16, the enhancer is active in four pairs of cardiac cells in most segments (Fig. 3C). In contrast, an enlarged heart was seen in embryos with ectopic pnr expression (Fig. 3D). These results demonstrate that Pnr can activate the D-mef2 heart enhancer and forced expressed of the protein culminates in increased numbers of cells in the dorsal vessel.

With an enlargement of the heart in embryos with ectopic pnr expression, it was of interest to determine the identity of the additional cells. D-MEF2 protein, bagpipe (bap) RNA (Azpiazu and Frasch, 1993) and the E2-3-9 enhancer trap insertion (Hartenstein and Jan, 1992) detect cardial cells in the heart. These markers were used to assess the relative numbers of cells in pnr-expressing embryos as compared to wild type. All markers showed a considerable increase in cardiac cell count within the heart tube and throughout dorsal regions of the embryos (Fig. 3E-J). For example, an average 47% increase was observed in the number of D-MEF2-positive nuclei present within the dorsal vessel of pnr-expressing embryos. Thus, forced mesodermal expression of Pnr leads to an overproduction of cardiac cells.

With the generation of supernumerary cardial cells, we wanted to ascertain if this increased population occurred at the expense of other derivatives of the dorsal mesoderm. The use of diagnostic markers indicated the gain in cardiac cells was paralleled by reduced levels of staining for the other cell types. As D-MEF2 is expressed in all muscles in the embryo, it was used to assess the formation of dorsal body wall muscles. In the pnr-expressing embryos, a decrease and abnormal organization of these muscles was observed (Fig. 3F). Likewise, there was an average 40% diminution in the population of Eve pericardial cells based on the absence or reduction in the Eve-expressing cell clusters (Fig. 4B) and the pericardial cell-associated antigen detected by mAb3 also exhibited an abnormal expression pattern (Fig. 4D). Finally, there was an apparent loss of cells within the visceral mesoderm lineage based on the decreased levels of bap RNA (Fig. 4F) and the patchy expression of FasIII in visceral muscles (Fig. 4H). These results suggest there may be a recruitment of cells into the cardiac lineage at the expense of other dorsal mesodermal cell types. Also, since there is an increase of cardiac but not Eve-expressing pericardial cells in the hearts of ectopic pnr-expressing embryos, we propose that Pnr is functioning as a cell-specific cardiogenic factor within this genetic context.

**Mouse GATA4 can function as a cardiogenic factor in Drosophila**

Pnr and the GATA4 protein of mice share an 85% sequence identity in regions that include their two zinc finger domains that are involved in protein-protein interactions and DNA binding (Fig. 5A). Since GATA4 is expressed in the cardiac lineage and regulates several heart-expressed genes in
vertebrates, we wanted to test its ability to function in *Drosophila* embryos when expressed in the mesoderm. Using the *twi-Gal4* driver, we directed GATA4 expression in the mesoderm and monitored the activation of the *D-mef2* heart enhancer and the formation of cardial cells. As was observed with *Pnr*, forced expression of GATA4 results in a robust activation of the *D-mef2-lacZ* fusion gene in the dorsal mesoderm (Fig. 5B; compare to Fig. 3A). Additionally, GATA4 expression programs an overproduction of cardial cells in the dorsal vessel based on several diagnostic markers including the *D-mef2-lacZ* fusion gene (Fig. 5C; compare to Fig. 3C), D-MEF2 protein (Fig. 5D; compare to Fig. 3E) and the *E2-3-9* enhancer trap insertion (Fig. 5F). Based on the D-MEF2 staining, an average 17% increase in the number of cardial cells was observed in the

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**Fig. 4.** Reduction of non-cardial dorsal mesodermal cell types in embryos with forced expression of *pnr*. (A,C,E,G) WT, wild-type embryos; (B,D,F,H) UAS-*Pnr*, embryos expressing *pnr* in the mesoderm under the control of a *twi-Gal4* driver. Several probes were used to assess the status of various derivatives of the dorsal mesoderm. (A,B) anti-Eve, precursors of pericardial cells and body wall muscle DA1; (C,D) mAb3, pericardial cells of the mature dorsal vessel; (E,F) bap RNA, precursors of the visceral mesoderm; (G,H) anti-FasIII, visceral muscle cells. Open arrows indicate an absence of cells or reduced staining of markers.

**Fig. 5.** Cardiogenic function of the mouse GATA4 transcription factor in *Drosophila* embryos. (A) Schematic diagram of *Pnr* and GATA4 illustrating an 85% sequence identity over 114 and 111 amino acids of the proteins, respectively. zf1 and zf2 represent the conserved zinc finger domains of the two factors while h1 and h2 denote the two putative amphipathic helices of *Pnr*. (B) Stage 11 and (C) stage 16 embryos of the genotype *twi-Gal4; UAS-GATA4* stained for *lacZ* expression under the control of a *D-mef2* cardiac cell enhancer. (D) Stage 14 embryo of the same genotype stained for D-MEF2 protein. An average of 122 D-MEF2-positive nuclei are observed within the dorsal vessel of GATA4-expressing embryos (*n*=20). (E,F) Stage 16 wild-type and *twi-Gal4; UAS-GATA4* embryos, both carrying the *E2-3-9* enhancer trap insertion chromosome that results in β-galactosidase activity in subsets of cardial cell nuclei. The arrow points to a cluster with extra cardial cell nuclei within a segment of the dorsal vessel, while the arrowhead indicates extra cardiac cells located outside of the heart tube.
dorsal vessel of GATA4-expressing embryos. Overall, such enhancer regulation and cardial cell induction demonstrate that the mouse GATA4 protein can function as a cardiogenic factor in Drosophila. Since mouse GATA1 (data not shown) and Drosophila Serpent (D. Hoshizaki, personal communication) fail to function comparably in heart induction assays, specificity exists in these cardiogenic properties of Pnr and GATA4.

**Synergistic activity of the Tin and GATA factors in cardial cell specification**

Certain NK-2 class homeodomain and GATA family proteins have been shown to physically interact in their cooperative activation of gene expression in cell culture systems (Durocher et al., 1997; Lee et al., 1998; Sepulveda et al., 1998). To test the possibility that Tin and GATA factors could functionally interact in an embryological context, we expressed the tin, pnr and mGATA4 genes independently or in combination in Drosophila embryos. The driver line used was again twi-Gal4, which directs Gal4 expression in the mesoderm throughout embryogenesis and also transiently in cells of the mesoderm through stage 10 (Baylies and Bate, 1996). This latter region will give rise to midline cells of the central nervous system (CNS). To monitor aspects of cardiogenesis, we included in the various genetic backgrounds the HIA237 cardial cell-specific enhancer of D-mef2 linked to lacZ (Gajewski et al., 1997).

The results of such experiments are presented in Figure 6, with a focus on the expression of the cardiac marker in the non-mesodermal midline cells. When tin, pnr or mGATA4 are expressed alone in the twi enhancer-expressing cells, the D-mef2 heart enhancer is activated ectopically in the cephalic (tin; Fig. 6B) or dorsal (pnr and mGATA4; Fig. 6C,D) mesoderm. As Tin is a known regulator of this enhancer, it could be activating the D-mef2 sequence in the head region through its fortuitous interaction with a co-factor normally expressed in these cells. The results are striking when both Tin and either of the GATA factors are co-expressed under the control of the twi-Gal4 driver (Fig. 6E,F). The cardial cell marker is now activated in both the cephalic region and throughout the dorsal and ventral trunk mesoderm. Likewise, a strong ectopic expression of the D-mef2 heart enhancer is detected in ventral midline cells of the developing CNS. The data point to a combinatorial interaction of Tin and the two GATA factors in the de novo activation of the cardial cell marker in both...
mesodermal and non-mesodermal cells. They also suggest these genetic combinations are inducing a cardial cell fate along the ventral midline of the CNS. In support, we observed the activation of the endogenous D-mef2 gene in ventral midline cells as well (Fig. 6G,H).

If cells are being directed into the cardiac lineage and away from a neural fate, genes normally transcribed along the ventral midline should be reduced in their expression. To test this prediction, we monitored the expression of the Single-minded (Sim) protein in wild-type embryos relative to those expressing the Tin-Pnr or Tin-GATA4 combinations. Sim is a HMLH class transcription factor that functions as a master regulator of CNS midline cell development (Nambu et al., 1990). In wild-type embryos, Sim is expressed in all midline cells (Fig. 6I). In contrast, an interrupted pattern of Sim was observed in embryos expressing Tin-Pnr (Fig. 6J) or Tin-GATA4 (Fig. 6K). The absence of this key regulator from cells along the ventral midline is consistent with such cells adopting a cardiac fate.

DISCUSSION

In this report, we demonstrate the Drosophila GATA gene pnr is expressed in the cardiogenic mesoderm where it has a crucial function in heart development based on its role in promoting the cardiac cell lineage while preventing the over-production of Eve-expressing pericardial cells. With the non-overlapping expression patterns of the Ladybird early and Eve proteins in cardiac and pericardial precursors, respectively, these lineages appear to arise from neighboring, yet distinct primordia within repeated parasegmental domains of the dorsal mesoderm (Azpiazu et al., 1996; Jagla et al., 1997). Possibly through interactions with different co-factors in the distinct progenitor types, the Pnr protein plays an instructive role in the formation of heart muscle cells and a repressive function in the production of Eve non-muscle cells. Thus, through combinatorial interactions, Pnr could carry out dual functions during the early stages of cardiogenesis. The ability of pnr to function as a transcriptional regulator of achaete and scute in the establishment of thoracic bristle pattern, mediated through genetic interactions with the u-shaped modulator gene, has been demonstrated previously (Haenlin et al., 1997; Garcia-Garcia et al., 1999).

tin gene function is also required for the specification of different cardiac cell types, but the expression domain of the gene is much broader than the limited regions of heart precursor formation (Azpiazu and Frasch, 1993; Bodmer, 1993). It has been proposed that tin endows the dorsal mesoderm with the competence to form the heart (and other derivatives), yet additional factors must work with the gene since ectopic tin expression does not result in the production of ectopic heart tissues (Yin and Frasch, 1998). The expression patterns and cardiac phenotypes of the wg and sloppy paired genes are consistent with one or both of the genes being centrally involved in the spatially restricted production of heart precursors along the embryonic anteroposterior axis (Lawrence et al., 1995; Wu et al., 1995; Azpiazu et al., 1996; Park et al., 1996; Jagla et al., 1997; Riechmann et al., 1997; Gajewski et al., 1998). However, the function of at least one additional component must be invoked for the formation of heart cells in the dorsalmost part of the mesoderm. Based on genetic results presented in this study, Pnr can function as a cardiogenic factor that works combinatorially with Tin to specify the cardial cell fate.

Our prior analysis of a cardial cell enhancer of the D-mef2 gene showed that both Tin and GATA sequence elements were required for proper cardiac cell expression (Gajewski et al., 1997, 1998). This work predicted the existence of a heart-expressed GATA factor in flies and the robust activation of D-mef2-lacZ reporters in embryos with forced expression of pnr argues strongly for this protein being a direct activator of the enhancer. In the ectopic Pnr-expressing embryos, enhancer activation and cardiac cell formation are not restricted to the dorsalmost part of the mesoderm, but appear to coincide with the broader domain of tin gene expression. It is possible that, in wild-type embryos, Pnr activity is limiting while Tin is in excess, leading to normal levels of enhancer expression and cardiac cell formation in the dorsalmost mesoderm. However, when Pnr is induced and maintained at high levels throughout the mesoderm, it could then act coordinately with Tin to turn on shared target genes and induce supernumerary cardial cells in an expanded cardiogenic domain. When both factors are expressed simultaneously, the D-mef2 enhancer is activated and the cardial cell specification program is induced in mesodermal and neural cell types. Taken together, these results indicate that, in the presence of tin function and other genetic inputs, pnr can function as a cardial cell identity gene.

In vertebrates, the GATA4, GATA5, and GATA6 transcription factors are expressed in overlapping patterns during heart development with transcripts from all three genes detected in the early precardiac mesoderm (Arceci et al., 1993; Kelley et al., 1993; Heikinheimo et al., 1994; Lavriere et al., 1994; Jiang and Evans, 1996; Morrissey et al., 1996, 1997; Jiang et al., 1998). Considering also the extensive studies on the ability of these proteins to activate cardiac gene expression in cultured cells (Grepin et al., 1994; Ip et al., 1994; Molkentin et al., 1994; Durocher et al., 1997; Murphy et al., 1997; Lee et al., 1998; Sepulveda et al., 1998), it is likely that one or more of these factors play a pivotal role in controlling cardiomyocyte specification. However, all three genes have been individually mutated in mice and phenotypic studies to date have failed to demonstrate a requirement for any of the transcriptional regulators in cardiac lineage commitment. GATA4 null mice form bilateral heart tubes that fail to fuse at the ventral midline, yet these tubes contain differentiated cardiomyocytes that express numerous cardiac structural genes (Kuo et al., 1997; Molkentin et al., 1997). GATA5 null mice are viable (Molkentin et al., 1997) and GATA6 mutant embryos die shortly after implantation, a result that precludes the analysis of a potential heart phenotype (Morrisey et al., 1998; Koutsourakis et al., 1999). It is possible that functional redundancies exist among the genes and the unmasking of a cardiac specification defect may only occur through the analysis of animals harboring combinations of null and conditional mutant alleles.

The use of the Gal4/UAS expression system (Brand and Perrimon, 1993) has allowed us to develop an assay to test the ability of genes to promote cardiac cell formation. Pnr and mouse GATA4 share an 85% amino acid identity within their zinc finger dimerization and DNA-binding domains. These regions have also been shown to mediate protein-protein interactions with heterologous transcription factors (Durocher
et al., 1997; Haenlin et al., 1997; Tsang et al., 1997; Lee et al., 1998; Molkentin et al., 1998; Sepulveda et al., 1998; Svensson et al., 1999; Tevosian et al., 1999). Based on the ability of pnr to activate the D-mef2 heart enhancer, cause cardiac hyperplasia and synergize with tin in inducing cardiac cell markers, we tested the capacity of mGATA4 to function similarly. The GATA4 protein can perform like Pnr in all of these processes, indicating it can function as a cardiogenic factor in the Drosophila system. Given these results, it will be of interest to test the ability of GATA4 to rescue phenotypes associated with pnr loss-of-function, including heart defects and other non-mesodermal developmental abnormalities. In contrast to GATA4, the non-heart expressed GATA1 protein is inactive in heart induction assays even though it shares a 76% amino acid identity with Pnr throughout their conserved domains. The molecular basis of this specificity is currently unknown, but the analysis of systematically altered forms of the GATA factors should provide insights into their functional characteristics.

In summary, the discovery of early heart phenotypes in pnr mutant embryos, coupled with the demonstration of uniquely conserved cardiogenic abilities of Pnr and GATA4, provide novel evidence for the function of GATA family members in the specification of a heart cell type. In an embryological context, these proteins can work with the Tin homeodomain factor to program cells into an apparent cardiac fate in both mesodermal and non-mesodermal cell types. This genetic combination appears to be essential, but not necessarily sufficient, for cellular commitment to the cardiac lineage as other factors may contribute to the specification process. Additional studies using the Drosophila cardiogenic assay should prove instrumental in revealing other key members of this genetic program.

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