Mutual genetic antagonism involving GLI3 and dHAND prepatterns the vertebrate limb bud mesenchyme prior to SHH signaling

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The bHLH transcription factor dHAND is required for establishment of SHH signaling by the limb bud organizer in posterior mesenchyme, a step crucial to development of vertebrate paired appendages. We show that the transcriptional repressor GLI3 restricts dHAND expression to posterior mesenchyme prior to activation of SHH signaling in mouse limb buds. dHAND, in turn, excludes anterior genes such as GLI3 and Alx4 from posterior mesenchyme. Furthermore, genetic interaction of GLI3 and dHAND directs establishment of the SHH/FGF signaling feedback loop by restricting the BMP antagonist GREMLIN posteriorly. These interactions polarize the nascent limb bud mesenchyme prior to SHH signaling.

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Development of paired appendages (limbs and fins) in vertebrates is controlled by a mesenchymal organizer located at the posterior limb bud margin (Johnson and Tabin 1997). Analysis of chicken and mouse limb bud development has shown that Sonic Hedgehog (SHH) is the morphogenetic signal expressed by the organizer (called polarizing region, or ZPA) that controls patterning of the distal limb bud (Chiang et al. 2001, Kraus et al. 2001). During progression of limb bud development, the polarizing region is maintained and propagated distally by an SHH/FGF signaling feedback loop. The SHH/FGF feedback loop is established in the posterior mesenchyme through localized activation of the BMP antagonist GREMLIN, which relays the SHH signal from responding mesenchymal cells to FGFs expressed by the posterior apical ectodermal ridge (AER; Zuniga et al. 1999, Sun et al. 2000). In turn, FGF signaling by the posterior AER maintains the SHH signaling polarizing region (Johnson and Tabin 1997). Interestingly, both GREMLIN in the posterior mesenchyme and FGFs in the posterior AER are activated prior to SHH signaling (Zuniga et al. 1999), similarly to other posterior genes such as S’HoxD genes (Kraus et al. 2001). These studies indicate that the nascent limb bud mesenchyme is already prepatterned (Chiang et al. 2001) and that the mesenchymal responsiveness to polarizing region signals is established prior to SHH activation. However, little is known about the mechanism acting upstream of SHH signaling to polarize the limb field and early limb bud. Several studies suggest a possible combinatorial involvement of Hox genes in positioning and polarizing the early limb field in response to retinoic acid (Lu et al. 1997). In particular, anterior ectopic expression of Hoxb8 in forelimb buds of transgenic mouse embryos results in establishment of an ectopic polarizing region and mirror image duplication of distal limb structures (Charité et al. 1994). However, neither targeted inactivation of the Hoxb8 gene (van den Akker et al. 1999) nor deletion of all Hox8 paralogs in the mouse alters limb morphogenesis (van den Akker et al. 2001).

In contrast, analysis of the basic helix–loop–helix (bHLH) transcription factor dHAND (or HAND2) in zebrafish (Yelon et al. 2000), chicken (Fernandez-Teran et al. 2000), and mouse embryos (Srivastava et al. 1997; Charité et al. 2000) shows that dHAND is required for establishment of SHH signaling in both fin and limb buds. During embryonic development, dHAND is initially expressed throughout the flank mesenchyme and becomes restricted to the posterior mesenchyme during initiation of limb bud development (for review, see Cohn 2000). Therefore, identification of the gene(s) restricting dHAND to the posterior limb bud mesenchyme should provide insights into the genetic networks acting upstream of the polarizing region.

Disruption of the zinc finger protein GLI3 in the mouse results in establishment of a small anterior ectopic polarizing region and a polydactylyous Extratoes (Xt) limb phenotype (Schimmang et al. 1992; Hui and Joyner 1993; Buscher et al. 1997). Normally, the full-length GLI3 zinc finger protein is processed to a transcriptional repressor (Wang et al. 2000), which participates in maintaining posterior restriction of SHH signaling during limb bud morphogenesis. SHH signaling by the polarizing region, in turn, inhibits the constitutive processing of GLI3, which results in formation of an anterior (high) to posterior (low) GLI3-R protein gradient (Wang et al. 2000). In addition to these reciprocal SHH–GLI3 interactions, genetic evidence for early GLI3 functions in establishing the polarizing region was also obtained (Zuniga and Zeller 1999). GLI3 is a part of a larger number of genes whose disruption in the mouse results in establishment of an anterior SHH signaling center in limb buds and polydactyly (Masuya et al. 1995, 1997; Qu et al. 1997). Only a few of the disrupted genes have been identified, for example, the paired homeodomain transcription factor Aristalless-like (Alx4). Disruption of the Alx4 gene in the mouse causes Strong’s Lupoid (Lst) polydactyly, and it has been proposed that ALX4, like GLI3, is part of the genetic mechanism that keeps SHH signaling restricted to the posterior limb bud mesenchyme (Qu et al. 1997; Takahashi et al. 1998).

In the present study, we establish that GLI3 is required to restrict dHAND expression to the posterior mesenchyme.

[Key Words: Alx4; dHAND; GLI3; limb development; polarizing region; SHH signaling]
chyme during initiation of limb bud morphogenesis. We also show that up-regulation of Alx4 expression depends on GLI3 function, thereby establishing that GLI3 acts initially upstream of ALX4. In turn, posterior dHAND function is required to keep both GLI3 and ALX4 restricted to anterior limb bud mesenchyme. Furthermore, dHAND positively regulates Gremlin expression and thereby differential responsiveness to SHH signaling, which, in turn, triggers establishment of the SHH/FGF feedback loop. Our studies reveal that the nascent limb bud mesenchyme is prepatterned by these genetic interactions prior to polarizing region signaling.

Results

GLI3 restricts dHAND to the posterior limb bud mesenchyme during initiation of limb bud outgrowth

dHAND is initially expressed throughout the lateral plate mesenchyme (Charité et al. 2000; Fernandez-Teran et al. 2000), but is restricted to the posterior mesenchyme during initiation of forelimb bud development by embryonic day 9.25 (E9.25; 22–23 somites; Fig. 1A). This correlates with activation of GLI3 expression in the anterior limb bud mesenchyme [Fig. 1B, see also Masuya et al. 1997; Zuniga and Zeller 1999]. Therefore, the distribution of dHAND was determined in forelimb buds of Xt/Xt homozygous embryos, which lack GLI3 function (Schimmang et al. 1992; Hui and Joyner 1993). In contrast to the rapid posterior restriction in wild-type limb buds [Fig. 1A, arrowheads], dHAND expression persists in anterior mesenchyme of GlI3-deficient limb buds [22–23 somites; Fig. 1C]. During progression of limb bud development, dHAND remains expressed in the anterior limb bud mesenchyme of Xt/Xt embryos [27 somites; Fig. 1, cf. E and D]. In GlI3-deficient limb buds, dHAND expression is lower in anterior than in posterior mesenchyme [Fig. 1E, open arrowhead] as dHAND expression is up-regulated under the influence of SHH signaling (Charité et al. 2000; Fernandez-Teran et al. 2000). Shh expression is first detected in posterior forelimb bud mesenchyme around E9.5 [25 somites; Masuya et al. 1997; data not shown]. The observed polarized expression of GlI3 [25 somites; Fig. 2A] and dHAND [Fig. 2B] is initially SHH-independent, as their complementary distribution is maintained in Shh-deficient limb buds [25 somites; Fig. 2C,D]. During subsequent limb bud development, SHH signaling in posterior mesenchyme regulates GlI3 expression negatively (Marigo et al. 1996) and dHAND positively (Charité et al. 2000; Fernandez-Teran et al. 2000). In older Shh-deficient limb buds, GlI3 is no longer excluded from anterior-most mesenchyme [Fig. 2E; see also Chiang et al. 2001], whereas the dHAND domain fails to extend distally [cf. Fig. 2F to 1D; see also Charité et al. 2000].

Expression of the transcription factor Alx4 is activated in anterior limb bud mesenchyme with kinetics similar to GlI3. Therefore, the possibility that ALX4 could participate in restricting dHAND was also studied [Fig. 2G–L]. In the absence of ALX4 function in Lst/Lst mouse embryos [25 somites], both posterior restriction of dHAND [Fig. 2, cf. G and H] and expression of GlI3 [data not shown] are normal. In contrast, comparative analysis of Alx4 in wild-type and Xt/Xt mutant limb buds shows that Alx4 expression is initially lower in GlI3-deficient limb buds [25 somites; Fig. 2, cf. I and J]. Subsequently, Alx4 expression remains relatively restricted in Xt/Xt mutant limb buds [34 somites; Fig. 2, cf. K and L]. The results presented in Figures 1 and 2 show that GLI3 represses dHAND and is necessary for positive regulation of Alx4 in anterior mesenchyme.

dHAND keeps both GLI3 and ALX4 anteriorly restricted during onset of limb bud outgrowth

Previous analysis of dHAND mutant mouse embryos has established that morphogenesis of their limb buds is disrupted at an early stage. dHAND-deficient limb buds appear slightly smaller than their wild-type counterparts, and activation of both 5’HoxD genes and Shh around E9.5 is disrupted (Charité et al. 2000; Yelon et al. 2000). To assess whether expression of anterior genes is also altered in dHAND mutant limb buds, the distributions of GlI3 and ALX4 were analyzed. Whereas GlI3 is normally not expressed by posterior mesenchymal cells [Fig. 3A,C, arrowhead; see also Fig. 1B], it is expressed by posterior-most mesenchyme in dHAND-deficient forelimb buds from early stages onward [Fig. 3B,D, arrowhead]. Similar to GlI3, the expression of Alx4 is no longer restricted to the anterior-most mesenchyme [Fig. 3E], but is expanded posteriorly in dHAND-mutant limb buds [Fig. 3F]. Taken together, these results show that both GlI3 and Alx4 are aberrantly expressed in posterior mesenchyme of dHAND mutant limb buds.
However, one possible explanation for the observed nonpolarized $Gli3$ and $Alx4$ expression could be the posteriors of mesenchyme. $Hoxb8$ is the earliest known marker for the posterior part of the forelimb field (Charité et al. 1994). By E9.5 [24–25 somites], weak $Hoxb8$ expression is still observed in the posterior half of both wild-type and $dHAND$ mutant forelimb buds [Fig. 3G,H], which shows that posterior mesenchyme is not lost in $dHAND$ mutant limb buds at this stage. As $dHAND$ is essential for survival of mesenchymal cells (Srivastava et al. 1997), TUNEL staining was used to assess a possible contribution of apoptosis to these early alterations of gene expression patterns. Analysis of serial sections revealed that no significant increase in cell death has occurred in the mesenchyme of both wild-type and $dHAND$ mutant forelimb buds by E9.5 [24–25 somites; Fig. 3I,J], when expression of $Gli3$ and $Alx4$ has already been expanded posteriorly [Fig. 3B,D,F]. However, the mesenchyme of $dHAND$ mutant limb buds begins to undergo massive apoptosis by E9.75 [27 somites and older; data not shown]. In summary, the results shown in Figure 3 establish that $dHAND$ function is required to exclude $Gli3$ and $Alx4$ from the posterior limb bud mesenchyme.

The reciprocal $Gli3$–$dHAND$ interactions participate in establishing differential responsiveness to future SHH signaling

The BMP antagonist GREMLIN participates in relaying the SHH signal from the mesenchyme to the AER during establishment and maintenance of the SHH/FGF feedback loop. Activation of Gremlin in the limb bud mesenchyme and $Fgf$ expression in the posterior AER precedes SHH signaling (Zuniga et al. 1999). Interestingly, the expression of both Gremlin [Fig. 4B,D] and $Fgf4$ [Fig. 4F] is anteriorly expanded in $Xt/Xt$ limb buds [Fig. 4, cf. A,C,E to B,D,F]. This anterior expansion has occurred by E9.75 [29–30 somites; Fig. 4B] and precedes detection of ectopic anterior SHH signaling in $Xt/Xt$ limb buds by ~1 embryonic day (Buscher et al. 1997; Zuniga and Zeller 1999). In contrast, Gremlin expression is normal in $Alx4$-deficient limb buds during the same developmental period [data not shown].

One possible cause for this anterior expansion of Gremlin could be its up-regulation by ectopic $dHAND$ function [Fig. 1]. However, $dHAND$ is not necessary for Gremlin activation, as...
Retroviral overexpression of dHAND top (n the anterior mesenchyme (arrowhead) in all embryos analyzed. Results in similar up-regulation of Gremlin els expression in limb buds contralateral to the ones shown in panels A and D. [E, F] Fgf4 expression in the limb buds contralateral to the ones shown in panels C and D. [G] Retroviral overexpression of dHAND in chicken limb buds results in similar up-regulation of Gremlin expression in the anterior mesenchyme (arrowhead) in all embryos analyzed (n = 6). All limb buds shown are forelimb buds, with anterior to the top and posterior to the bottom.

Figure 4. Genetic interaction of GLI3 and dHAND restricts GREMLIN-mediated competence to establish the SHH/FGF signaling feedback loop to the posterior limb bud mesenchyme. (A) Gremlin expression in a wild-type limb bud (29–30 somites). (B) Gremlin expression expands anteriorly in an Xt/Xt limb bud (29–30 somites). (C) Gremlin expression in a wild-type limb bud (37 somites). (D) Gremlin expression in an Xt/Xt limb bud (37 somites). [E, F] Fgf4 expression in the limb buds contralateral to the ones shown in panels C and D. [F] Xt/Xt limb bud (37 somites). [G] Retroviral overexpression of dHAND in chicken limb buds results in similar up-regulation of Gremlin expression in the anterior mesenchyme (arrowhead) in all embryos analyzed (n = 6). All limb buds shown are forelimb buds, with anterior to the top and posterior to the bottom.

Figure 5. Reciprocal genetic repression between GLI3 and dHAND prepatterns the limb bud mesenchyme prior to activation of SHH signaling. (1) GLI3 repressor activity (GLI3-R) restricts expression of the bHLH transcription factor dHAND to the posterior mesenchyme during onset of limb bud morphogenesis. (2) GLI3-R participates in positive transcriptional regulation (dashed arrow) of another anterior transcription factor, Alx4. (3) dHAND is necessary to keep GLI3 and Alx4 expression restricted to the anterior mesenchyme. (4) In posterior mesenchyme, dHAND is necessary for activating expression of posterior genes, among them S’HoxD genes, Shh, and Bmp2. [for details and references, see text]. These genetic interactions prepattern the limb bud mesenchyme independent of SHH signaling.
loop [Zuniga and Zeller 1999; Zuniga et al. 1999]. Therefore, loss of posterior restriction of dHAND in Gli3-deficient limb buds is a likely cause of the anterior expansion of the Shh expression domain. This expansion long precedes establishment of a small anterior Shh signaling center. The analysis of Shh-deficient limb buds led Chiang et al. [2001] to conclude that the nascent limb field and early limb bud mesenchyme are prepatterned by an SHH-independent mechanism. The present study begins to uncover the molecular basis of this prepatterning mechanism and establishes that active cross-regulation between anterior and posterior mesenchyme is essential during initiation of limb bud outgrowth [Fig. 5]. This prepatterning mechanism participates in determining posterior identity and positioning of the polarizing region and sets up differential mesenchymal responsiveness to future SHH signaling. As GLI3 functions first to restrict dHAND expression to posterior mesenchyme, establishment of the limb bud organizer seems triggered by anterior to posterior repression of activators rather than solely by posterior activation.

Materials and methods

Mouse strains and embryos

Gli3-deficient mouse embryos were obtained by intercrossing heterozygous mice carrying the Xi allele. The 3’ part of the Gli3 gene is deleted in the Xi allele, and mutant embryos were PCR-genotyped as described by Buscher et al. [1997]. Axl-deficient mouse embryos were obtained by intercrossing heterozygous mice carrying the Lst allele. Lst-1 embryos were PCR-genotyped using a strategy based on the 16-bp deletion within the homeobox domain of the Ax1 gene (Takeda et al. 1998). dHAND-deficient embryos were obtained by intercrossing dHAND heterozygous mice and genotyped as described by Srivastava et al. [1997]. Shh-deficient embryos were obtained by intercrossing heterozygous Shh mice and genotyped as described by St-Jacques et al. [1998].

Whole-mount in situ hybridization

Whole-mount in situ hybridization using digoxigenin-labeled RNA probes was performed as described by Haramis et al. [1995]. The chicken Gremlin probe was isolated by RT-PCR and its identity confirmed by DNA sequencing. Wild-type and mutant embryos were age-matched according to their somite number [variation ±2 somites]. Reproducibility of all results was ensured by analyzing several embryos (n ≥ 3) in independent experiments.

Retroviral infection of chicken wing buds

RCAS-dHAND retroviral particles were injected into the presumptive wing field of chicken embryos (stage 12-14), and embryos were analyzed by in situ hybridization 3 days later (stage 25), as described in detail by Fernandez-Teran et al. [2000]. Pathogen-free eggs (CRIFFA) were used for all studies, and embryos were staged according to Hamburger and Hamilton [1951].

Detection of apoptotic cells by TUNEL staining

Apoptotic cells were detected in situ by incorporating fluorescein-dUTP into fragmented DNA using terminal transferase according to the manufacturer’s instructions [Roche Diagnostics].

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