Genetics of shoulder girdle formation: roles of Tbx15 and aristaless-like genes

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Summary

The diverse cellular contributions to the skeletal elements of the vertebrate shoulder and pelvic girdles during embryonic development complicate the study of their patterning. Research in avian embryos has recently clarified part of the embryological basis of shoulder formation. Although dermomyotomal cells provide the progenitors of the scapular blade, local signals appear to have an essential guiding role in this process. These signals differ from those that are known to pattern the more distal appendicular skeleton. We have studied the impact of Tbx15, Gli3, Alx4 and related genes on formation of the skeletal elements of the mouse shoulder and pelvic girdles. We observed severe reduction of the scapula in double and triple mutants of these genes. Analyses of a range of complex genotypes revealed aspects of their genetic relationship, as well as functions that had been previously masked due to functional redundancy. Tbx15 and Gli3 appear to have synergistic functions in formation of the scapular blade. Scapular truncation in triple mutants of Tbx15, Alx4 and Cart1 indicates essential functions for Alx4 and Cart1 in the anterior part of the scapula, as opposed to Gli3 function being linked to the posterior part. Especially in Alx4/Cart1 mutants, the expression of markers such as Pax1, Pax3 and Scleraxis is altered prior to stages when anatomical aberrations are visible in the shoulder region. This suggests a disorganization of the proximal limb bud and adjacent flank mesoderm, and is likely to reflect the disruption of a mechanism providing positional cues to guide progenitor cells to their destination in the pectoral girdle.

Key words: Aristaless-like genes, Gli3, Mouse mutants, Pax genes, Scapula, Skeletogenesis, Tbx15

Introduction

Although insight into the essentials of limb patterning has been rapidly increasing in recent years (Niswander, 2003), the development of the shoulder and pelvic girdle has remained more elusive. The much-studied signaling centers that are responsible for patterning of the limb bud often have little or no impact on the formation of shoulder or pelvis, and many of the classical or artificially made mutants that show an affected limb phenotype have normal skeletal elements of the girdles. However, studies involving the manipulation of chick embryos have greatly advanced our understanding of the embryology of shoulder formation. For instance, Huang and coworkers (Huang et al., 2000) identified a set of eight dermomyotomes as the origin of the scapular blade, whereas, by contrast, the scapular head derives from the somatopleure. It also became clear that signals from the surface ectoderm provide essential instructive signals (Ehehalt et al., 2004).

Relatively few mutants display disturbed pectoral girdle development, and even less show total absence of one or more elements. Pellegrini et al. reported a total lack of the scapula blade and ilium in Emx2 mutants, whereas the remainder of the limb remained mostly intact (Pellegrini et al., 2001). Despite this striking observation it was recently concluded from detailed functional analyses in chick that Emx2 is not sufficient for inducing shoulder structures (Pröls et al., 2004). These authors described its role as providing positional signals to cells fated to contribute to the skeletal elements of the shoulder. Loss of function of the forelimb-specific gene Tbx5 can lead to total absence of the limb, including the scapula (Ahn et al., 2002; Ng et al., 2002; Rallis et al., 2003; Takeuchi et al., 2003). As this phenotype resulted from an experimental design where loss of function was restricted to limb bud mesoderm, it was suggested that a disturbed recruitment of cells caused the absence of the scapula (Rallis et al., 2003). Both of these examples underscore the notion that – even after the correct laying down of progenitor structures – disruption of positional cues may suffice to totally ablate skeletal elements of the shoulder.

Genes functionally linked to shoulder formation by less dramatic phenotypes in loss-of-function mutants include the Paired box gene Pax1, which is allelic with the classical undulated mutant (Balling et al., 1988), Hoxa5 (Aubin et al., 1998), the mutant of which has a reduced acromion, Pbx1, the mutant of which has a reduced scapular blade (Selleri et al., 2001), and the Polycomb homolog M33, the mutant of which
has a hole in the scapular blade (Core et al., 1997). Such a scapular foramen may also be present in embryos homozygous for the Extra toes (Xt) mutation, which is allelic with Gli3 (Hui and Joyner, 1993; Johnson, 1967), and with near-complete penetrance in de (droopy ear) mutants (Curry, 1959). We recently demonstrated that de is allelic with Tbx15 (Candille et al., 2004). Very recently, and after the first submission of the present manuscript, a very thorough description of the skeletal phenotype of de was published (Singh et al., 2005).

Here we show that the aristaless-related genes Alx4 and Cart1 – previously linked to functions in limb and craniofacial development (Qu et al., 1999; Beverdam et al., 2001; Meijlink et al., 2003) – are implicated in shoulder girdle development, a role that was previously concealed by the redundancy of their functions. We investigated in more detail the phenotype of Tbx15 mutants, exploring its genetic interactions with Gli3, Alx4 and Cart1. In spite of the similar scapular phenotypes of Gli3 and Tbx15 mutants, the very strong defect seen in Tbx15/Gli3 embryos suggests a synergistic functional relationship between these two genes. By contrast, the phenotype seen in Tbx15/Alx4/Cart1 triple mutants appears to be a mere addition of phenotypes seen in the single mutants. This suggests complementary functions, and a connection to parallel processes of Gli3 on the one hand, and to Alx4 and Cart1 on the other. Expression of several genes that represent markers for the different cell types contributing to the shoulder elements, including the chondrocyte marker Pax1, were affected in Gli3, Tbx15 and Alx4/Cart1 mutants. Strikingly, in Alx4/Cart1 mutants Pax1 expression was ventrally shifted. In addition, the myogenic marker Pax3, whose expression domain does not overlap with that of Alx4 and Cart1, was abnormally expressed in Alx4/Cart1 but not Tbx15 or Gli3 mutants. These results appear to point to a disruption of local signals, implying that in these mutants, ectopic positional cues are causative of the skeletal defects.

Materials and methods

Mutant mice lines

Tbx15 (de/s), Alx4 (Lt/s) and Gli3 (Xc/s) mutant mice were originally obtained from the Jackson Laboratory (Bar Harbor, Maine, USA). Alx3 mutant mice were generated in our laboratory (Beverdam et al., 2001). Cart1 mutant mice were obtained from B. de Crombrugghe, Houston, Texas (Zhao et al., 1996). All experiments were conducted under the approval of the animal care committee of the KNAW (Netherlands Royal Academy of Arts and Sciences). Genotyping was done by PCR on ear cuts or yolk sac DNA. Tbx15, Alx3, Alx4, Cart1 and Gli3 embryos and mice were genotyped as described previously (Candille et al., 2004; Beverdam et al., 2001; Te Welscher et al., 2002).

Mice were bred in a mixed genetic background. Most of the phenotypes observed were influenced by this variable background, but this variability was minor when compared with the morphological consequences seen in comparisons between single and double mutants. Moreover, conclusions on genotype-phenotype relationships were always based on, or consistent with, comparisons of embryos within one litter, in which the contribution of alleles of unlinked modifier genes should be essentially identical.

Nomenclature and definitions

For the sake of simplicity, throughout this paper we refer to de mutants as ‘Tbx15 mutants’, to Lt mutants as ‘Alx4 mutants’, and to Xc mutants as ‘Gli3 mutants’. The terms anterior and posterior with respect to the scapular blade may seem ambiguous, but refer in this paper to supraspinatus fossa and infraspinatus fossa, respectively.

Analysis of embryos and newborn mice

Bone and cartilage staining was done essentially as described (Beverdam et al., 2001). Whole-mount in situ hybridization using digoxigenin-labeled RNA probes was performed as described (Leussink et al., 1995; Ten Berge et al., 1998a), and in situ hybridization on sections was essentially as described (Gregoireff et al., 2004). Probes used included Alx4, Gli3 (Te Welscher et al., 2002), Pax1 (Ballinger et al., 1988), Pax3 (Goulding et al., 1991), En2 (Simeone et al., 1992), Scleraxis (Cserjesi et al., 1995) and Tbx15. To prepare a Tbx15 in situ probe, a 762-bp fragment corresponding to part of the last exon was PCR-amplified from genomic DNA and subcloned in a pGEM-T vector (Promega, Madison, WI). Primers used were 5'-CCCTTCAACTAAATCAGC-3' (forward) and 5'-GAAGCCAAGTGCCAGTACG-3' (reverse).

Proliferating cells were detected using rabbit anti-phospho-histone H3 (Upstate, Charlottesville, VA, USA), according to manufacturer’s protocol. Cells in equal areas of controls and mutants were counted and the average number compared. Apoptotic cells were detected using rabbit anti-cleaved Caspase-3 (Cell Signaling, Beverly, MA, USA), according to manufacturer’s protocol. For Nile Blue (Sigma) staining, embryos were dissected and directly stained in 2 ml of DMEM culture medium containing 2 µl of 1.5% Nile Blue at 37°C, then washed with PBS for several hours and photographed.

Results

Skeletal malformations in Tbx15 mutants

We recently reported that a 216-kb deletion in the Tbx15 gene causes the droopy ear (de) mutation, and explored Tbx15 function in dorsoventral patterning of pigmentation (Candille et al., 2004). Here, we have studied aspects of the skeletal phenotype of this mutant. Figure 1 shows characteristic features of Tbx15 expression that may be relevant to the skeletal abnormalities seen in de mutants (Agulnik et al., 1998; Candille et al., 2004; Singh et al., 2005); expression of a zebrafish orthologue was also reported (Begemann et al., 2002). Expression was detected in mesenchyme of the limb buds from embryonic day (E) 9.5 (not shown) and, at E10.5, was seen to be highest in a medial-proximal domain (Fig. 1A). At later stages it appears to demarcate the developing zeugopodal elements (shown for the hind limbs at E11.5; Fig. 1B). In the head, it is expressed in lateral mesenchyme near the surface ectoderm (Fig. 1K). In the mandibular arch, it is expressed in two bilateral spots of mesenchyme adjacent to the ectoderm at the caudal side of the arch. Tbx15 is also expressed in the notochord, but unlike the archetypal T-box gene Brachyury, expression is restricted to the part of the notochord anterior from the caudal hindbrain. Expression extends from the notochord into the surrounding cranial mesenchyme (Fig. 1L).

To study skeletal abnormalities, we compared Alcian Blue/Alizarin Red stainings of newborn wild-type and Tbx15+/− mice; heterozygous mice were indistinguishable from wild types (not shown). Figure 2A-F shows abnormalities in the surface ectoderm (Fig. 1K). In the mandibular arch, it is expressed in two bilateral spots of mesenchyme adjacent to the ectoderm at the caudal side of the arch. Tbx15 is also expressed in the notochord, but unlike the archetypal T-box gene Brachyury, expression is restricted to the part of the notochord anterior from the caudal hindbrain. Expression extends from the notochord into the surrounding cranial mesenchyme (Fig. 1L).
the axis (2nd vertebra), where it forms the dens. In the Tbx15 mutants, these distinctive traits are partly lost: the dens of axis is reduced (arrowhead in Fig. 2D) and ectopic cartilage, including at this stage a tiny ossification centre, is present at a corresponding position (arrow) in the mutant atlas. It seems plausible that this aspect of the phenotype somehow relates to Tbx15 expression in notochord and surrounding mesenchyme (Fig. 1J,L), particularly as Curry had already noted a ‘double thickening of the notochord in the dens’ in Tbx15 mutant embryos at a stage (E16) when the notochord has ‘normally almost disappeared’ (Curry, 1959). The neural arches of Tbx15–/– skeletons exhibit various abnormalities, including an axis with widened arches along the anteroposterior direction (not shown). Comparison of the cranial base of wild-type versus Tbx15–/– mice (Fig. 2E,F) demonstrates that the Tbx15–/– skull is shorter and narrower than that of wild-type mice. This presumably causes, or contributes to, the abnormal position of the ears. We did not observe abnormal fusion of the supraoccipital and exo-occipital bones, as described by Curry. Tbx15 mutants also have a comparatively narrow basioccipital bone (B in Fig. 2F), combined with an abnormally medial and caudal location of the inner ear (I in Fig. 2F). In the lower jaw

Fig. 2. Skeletal abnormalities of Tbx15 mutants. Alcian Blue and Alizarin Red staining of newborn and E13.5 wild-type and Tbx15 mutants. (A) Newborn Tbx15 mutants have a foramen in the blade of the scapula and the humerus is shorter than in wild type. (B,C) Alcian Blue staining of E13.5 wild-type (B) and Tbx15 mutant (C) shoulder girdle. At this stage the phenotype is already present. (D) Abnormalities of the caudal posterior aspect of vertebrae in newborn Tbx15 mutants. Arrow indicates ectopic cartilage in the atlas of Tbx15 mutant; arrowhead indicates the place were the dens of the axis is missing. (E,F) Cranial base of a newborn wild-type (E) and Tbx15–/– (F) skull. The Tbx15 mutant skull is shorter and narrower than the wild type, and the basioccipital bone (B) is narrow when compared with wild type; also the inner ear (I) has an abnormal medial and caudal location.
of Tbx15+/–, the dentaries are also shorter, with a short angular process (not shown).

The most characteristic defect in Tbx15–/– mice is the scapular foramen (Fig. 2A-C). The mutant’s scapula is somewhat reduced in size compared with wild type and is more posteriorly and ventrally positioned. The scapular phenotype was already clearly visible at E13.5 (Fig. 2B,C), and at E12.5 was foreshadowed by an abnormal shape of the corresponding mesenchymal condensation. In addition, at E16.5 the acromium is reduced (black arrowhead in Fig. 3B).

Other parts of the skeleton do not show clear defects. In sharp contrast to the shoulder region, and in spite of very similar Tbx15 expression in both fore- and hindlimb bud regions (Agulnik et al., 1998) (Fig. 1), the pelvic girdle is normal (Fig. 4E). In contrast to Curry, we did not observe a significant generalized reduction in bone size. Differences in genetic background and/or the fact that that author studied a different allele of Tbx15 are likely to explain the weak expression of the phenotype in the animals in our study. The 100% penetrance of the scapular foramen emphasizes its significance and rules out the possibility that it is caused by merely a broad skeletogenic deficiency.

**Tbx15 and Gli3 act synergistically during shoulder girdle development**

Extra toes (Xt) mutants have a disrupted Gli3 gene (Schimmang et al., 1992; Hui and Joyner, 1993) and homozygosity of this mutation leads to a malformed shoulder girdle. Depending on genetic background, Gli3 homozygotes may contain a foramen in the scapular blade (Johnson, 1967; Hui and Joyner, 1993), thus resembling the droopy ear phenotype. If this similarity resulted from Gli3 and Tbx15 functioning in the same pathway(s) during shoulder formation, one would expect little exacerbation of the phenotype in double mutants. To investigate this, we generated Gli3–/–/Tbx15–/– homozygous compound mutants and compared the phenotypes of single and double mutants.

Skeletal staining of E16.5 fetuses showed a severe reduction of the scapular blade in Gli3–/–/Tbx15–/– mutants (Fig. 3F) when compared to either single mutant (Fig. 3B,C). Only the most anterior part of the scapular blade (supraspinatus fossa) remained, as well as a small part of the edge of the blade. Furthermore, the acromium was more severely reduced (arrowhead in Fig. 3B,D,F), whereas the glenoid fossa (scapular head) was normal. This aggravated shoulder...
phenotype is clearly dependent on gene dosage because the scapular foramen of \textit{Gli3}\textsuperscript{+/–}/\textit{Tbx15}\textsuperscript{+/–} mutants is enlarged in comparison with \textit{Tbx15}\textsuperscript{–/–} single mutants (compare Fig. 3B and 3D). Although we never observed a scapular foramen in the \textit{Gli3} mutants used in our study, the shoulder elements were broader than those in wild types, and contained indentations in the scapular blade (white arrowheads in Fig. 3C). In \textit{Tbx15}\textsuperscript{+/–}/\textit{Gli3}\textsuperscript{+/–} mutants these malformations were enhanced, the scapular blade was still broader and a foramen in the scapula was now present (Fig. 3E).

In conclusion, the phenotypes of compound mutants suggest that \textit{Tbx15} and \textit{Gli3} act synergistically during shoulder girdle formation, representing at some level a degree of functional redundancy.

**Functions of \textit{Alx3}, \textit{Alx4} and \textit{Cart1} in limb girdle development**

Previously, we, and others, have studied the roles of \textit{Alx3}, \textit{Alx4} and \textit{Cart1}, with an emphasis on limb and craniofacial development. These three genes have strongly overlapping functions in limb and craniofacial development (Qu et al., 1999; Beverdam et al., 2001) (also A.B., unpublished). We reported severe truncation of the collar bone (clavicle) of \textit{Alx3/Alx4} mutants, but not of either single mutant (Beverdam et al., 2001) (see Fig. 3T); otherwise these genes have not been linked to pectoral or pelvic girdle development.

Close inspection of the shoulder elements of \textit{Cart1} mutants revealed a slight reduction of the anterior blade in this single mutant, although the acromion was normal (Fig. 3H). In \textit{Alx4/Cart1} mutants (Fig. 3I,U), not only was the clavicle truncation much more severe than in \textit{Alx3/Alx4} mutants, but also the scapular blade rostral from the spine was virtually absent, and the spine itself and the acromion was shortened (arrowhead in Fig. 3I). Analyses of various compound genotypes showed similarly affected phenotypes in all double homozygous mutants (Fig. 3J); however, it was clear that inactivation of \textit{Cart1} had the most impact and that the impact of \textit{Alx3} mutation was much less. In conclusion, \textit{Cart1} has a major function in scapula formation that becomes clearly manifest only in the context of mutation(s) in \textit{Alx4}, with which it shares an overlapping function.

In contrast to \textit{Tbx15} mutants, and also not previously reported, the pelvic girdle of \textit{Alx4/Cart1} double mutants is affected as well. Although \textit{Alx3} and \textit{Cart1} single mutants were normal (not shown), we noticed that \textit{Alx4} mutants had a reduced pubic bone (arrowhead in Fig. 4B). However, the pubic bone was more severely affected in \textit{Alx3/Alx4} and \textit{Alx4/Cart1} compound mutants (Fig. 4C,D). Note that the ilium of the mutant was normal, and that the scapula and pubic bone serve non-analogous functions. Therefore, \textit{Alx3}, \textit{Alx4} and \textit{Cart1} have overlapping functions in the formation of elements of both the pectoral and pelvic girdle, but different structures are affected. By contrast, loss of function of, for example, \textit{Enm2} and \textit{Pbx1} affects the scapula and ilium in similar ways (Pellegrini et al., 2001; Selleri et al., 2001).

**Genetic relationship between \textit{Tbx15}, \textit{Alx4} and \textit{Gli3} mutants**

We generated \textit{Alx4/Cart1/Tbx15} mutant embryos to investigate possible genetic interactions in the way these genes pattern the shoulder girdle. Upon skeletal staining of \textit{Alx4/Cart1/Tbx15} triple mutants at E16.5, a severe reduction of the scapular blade was observed (Fig. 3N). The only remnants of the scapula were the glenoid fossa (scapular head), a small fraction of the acromion (arrowhead in Fig. 3N) and the posterior part of the blade (the infraspinatus fossa). The clavicle was completely absent, as is shown in an intact skeleton (Fig. 3O,P).

The severity of the phenotype depends on gene dosage as shown by intermediate phenotypes in a \textit{Tbx15}\textsuperscript{+/–}/\textit{Gli3}\textsuperscript{+/–} background. For example, in \textit{Cart1/Tbx15} compound mutants the hole in the scapula is larger than in \textit{Tbx15} homozygotes (Fig. 3L), and in \textit{Alx4}\textsuperscript{+/–}/\textit{Cart1}\textsuperscript{+/–}/\textit{Tbx15}\textsuperscript{+/–} the spine was more reduced, the scapular blade was more severely malformed than in \textit{Alx4/Cart1} mutants, and a tiny remnant of the clavicle was present (compare Fig. 3I and 3M, and Fig. 3U and 3V). These results demonstrate that \textit{Tbx15} acts cooperatively with \textit{Alx4} and \textit{Cart1} in the development of the scapula. Comparing phenotypes of single and double mutants does not necessarily imply synergism between aristaless-related and T-box genes, as it appears that the defects are largely additive.

Similarly, we generated \textit{Gli3/Tbx15} compound mutants. This not only allows the investigation of genetic interactions between these two genes, but also provides an opportunity to compare the impact on shoulder formation, of the \textit{Alx4} and \textit{Cart1} genes on the one hand and of the similarly expressed \textit{Gli3} gene on the other. \textit{Alx4/Cart1/Tbx15} triple mutants and \textit{Gli3/Tbx15} compound mutants show strikingly contrasting phenotypes. By and large, whereas \textit{Alx4/Cart1/Tbx15} homozygous triple mutants lacked the anterior part of the scapular blade, \textit{Gli3/Tbx15} double mutants lacked the posterior part of the blade (compare Fig. 3F and 3N). Therefore, against the background of deficient \textit{Tbx15} function, the different roles of \textit{Alx4} and \textit{Cart1}, when compared with \textit{Gli3}, become more conspicuous.
Gene regulation in shoulder mutants

To begin to clarify the molecular pathways underlying shoulder girdle development in mammals, we studied the expression of genes that are functionally linked to this process in Alx4, Cart1, Tbx15, and Gli3 single and compound mutants. First, we set out to study the expression patterns of Tbx15, Alx4, Cart1 and Gli3 in the mutants used in this study. Alx4 has previously been reported to be downregulated in the limb buds of Gli3 mutants; however, this concerns only the most distal part of the expression domain, which would therefore not be expected to be relevant for the phenotype of the scapula (Te Welscher et al., 2002) (see Fig. 1D,E). We observed that expression of Tbx15 in Alx4, Cart1 and Gli3 mutant limb buds at E10.5 and E11.5 was not altered, and neither was expression of Alx4 and Gli3 in Tbx15+/− mutant limb buds at E10.5 (data not shown).

Emsx2 has an essential role during shoulder development. It is normally expressed in the anterior-proximal region of the forelimb bud and at the base of the hindlimb bud. Its ablation leads to loss of both the scapula and the ilium (Pellegrini et al., 2001). Expression of Emsx2 was unaltered in Alx4/Cart1 single and double mutants, and in Tbx15/Gli3 single and double mutants (Fig. 1F-I), suggesting that Emsx2 acts in a parallel pathway or upstream of Alx4, Cart1, Gli3 and Tbx15.

Pax1 has a well-documented function in shoulder formation (Timmons et al., 1994; Dietrich and Gruss, 1995). In addition to being a sclerotome marker, Pax1 is normally expressed in mesenchyme in the anterior proximal part of the fore- and hindlimb bud (Timmons et al., 1994). We therefore studied Pax1 expression in various mutants with an affected shoulder phenotype. Expression of Pax1 was not altered in Alx4 and Cart1 single mutants at E10.5 (Fig. 5F,G). Strikingly, in Alx4+/−/Cart1−/− the expression of Pax1 in the limb bud was strongly reduced at the site of its normal expression (Fig. 5H) and was upregulated in the ventral body wall adjacent to the limb bud. Images from a different angle are required to demonstrate this shift: Fig. 5I-L show ventral aspects of the limb bud. Images from a different angle are required to demonstrate this shift; Fig. 5I-L show ventral aspects of the limb bud. Images from a different angle are required to demonstrate this shift. Histone 3, did not show significant differences between wild-type and mutant embryos either. In view of the implied non-overlapping expression patterns of the genes, another explanation for the aberrant expression of Pax1 would be that in Alx4/Cart1, and perhaps in Tbx15, mutants, positional cues have been disrupted, which may interfere with the normal recruitment of cells homing for the scapula region, eventually leading to malformations of skeletal elements of the shoulder girdle. To further investigate this, we analyzed the expression of Scleraxis and Pax3.

Although Pax1 is considered to be a marker of the chondrocyte lineage, Pax3 is thought to mark, in the context of limb development, the myogenic lineage. Recently, the syndetome was identified as a fourth component of the somite, consisting of tendon progenitors that are distinguished by expression of Scleraxis (Scx) as a marker (Brent et al., 2003). We compared the expression of Pax3 and Scx in limb buds of E10.75 Alx4/Cart1 mutant and wild-type embryos. From the whole-mount in situ hybridization experiment shown in Fig. 5V, it can be seen that Pax3 expression is shifted towards the antero-proximal region of the limb bud in a region where Pax1 is downregulated. In addition, hybridization of sections of Alx4/Cart1 mutants with Pax3 demonstrated that Pax3 expression in the body wall (marking myotonic progenitors from the dermomyotome and heading for the limb) is abnormally located in mesenchyme, just adjacent to surface ectoderm (Fig. 5S,T). Scx expression was changed to a lesser degree, but appeared to be elevated in the antero-proximal region of the limb bud in the Alx4/Cart1 mutant (green arrowhead in Fig. 5X). Fig. 5Y summarizes these results schematically. We conclude that different types of migrating cells that are bound to contribute to the pectoral girdle are disorganized in shoulder mutants at an embryonic stage prior to visible anatomical aberrations. Possibly it cell migration itself that is affected, but alternatively a transformation of cells involved may take place. By contrast, no ectopic expression of Pax3 or Scx was seen in Tbx15 mutants, or in Tbx15/Gli3 mutants (data not shown).

Discussion

The developmental pathways responsible for patterning of the skeletal elements in the mammalian pectoral and pelvic girdles have remained rather obscure. Extrapolation of experimental results obtained in grafting experiments in avian species suggests that the scapula derives from a set of dermomyotomes, whereas other elements would have a somatopleural origin. The paradoxical origin of an endochondral skeletal element like the scapula from dermomyotome has led to speculation that it arose during evolution by the ossification of muscles (Burke, 2000; Huang et al., 2000). If this is a correct representation of the ontogeny of these elements, it is understandable that the mechanisms that underlie their formation differ from those of the well-known signaling centers that shape the vertebrate. Indeed, many mutations that affect limb formation have little or no impact on the pectoral and pelvic girdles.

In this study, we have explored the genetic interactions of a number of genes that are implicated in formation of the pectoral (and to a lesser extent pelvic) girdle skeleton. The study of genotype-phenotype relations in complex compound mutants allows genetic relationships between genes to be determined, and the recognition of important gene
Aristaless-related genes

We show that *Cart1* and *Alx4* single mutants have slight, not previously reported, defects in skeletal elements of the pectoral and pelvic girdle, respectively, that become more severe in double mutants carrying additional mutations in either one of the three redundant genes *Alx3*, *Alx4* and *Cart1*. Whereas *Emx2* appears to be essential for the formation of structures of both girdles (scapula and ilium) that look superficially similar (Pellegrini et al., 2001), *Alx4/Cart1* mutants, as well as *Tbx15* mutants, have very different phenotypes in the shoulder and pelvis. There is no sound basis for describing both girdles in terms of homology; clearly evolution of the girdles has evolved separately and under different species-specific constraints. During evolution, the aristaless-related genes may have been recruited for different functions in development of both types of girdle. Any speculation on such topics is rather futile in the absence of both mutants from appropriate different species and expression data from extinct ancestors. The pubic bone is also affected in mutants for the aristaless-related genes *Prx1* and *Prx2* (Ten Berge et al., 1998b), which have overlapping but broader expression patterns and are generally linked to different phenotypes.
The prevailing function of Cart1 that emerges from comparing compound mutants involving Alx3, Alx4 and Cart1 is also unexpected because Cart1 is expressed only at low levels in mesoderm of the limb buds and flank (Zhao et al., 1994; Beverdam and Meijlink, 2001). This paradox was previously noted for the polydactyly in Alx4/Cart1 double mutants (Qu et al., 1999).

Distinct functions of Gli3 and Alx4 revealed in Tbx15 double mutants

The striking scapular foramen characteristic of Tbx15 mutants shows that this gene is essential for appropriate shoulder formation. Gli3 mutants kept in certain genetic backgrounds have a similar phenotype. The combined deficiency of these two genes, however, resulted in a unique phenotype in which the anterior part of the scapula remained, leaving a structure that resembled a typical long bone (e.g. Fig. 3F). Such an element also resulted from Alx4/Cart1/Tbx15 triple homozygous mutants (Fig. 3N), but in this case through ablation of the anterior part of the scapula. These contrasting phenotypes reveal complementary functions of Gli3 and Alx4/Cart1, linking Gli3 to the posterior part of the scapular blade (infraspinatus fossa), and Alx4 and Cart1 to the anterior part (supraspinatus fossa), as depicted in the schematic representation in Fig. 3W,X. Interestingly, Alx4 and Gli3 have strongly overlapping expression patterns in the anterior mesoderm of the limb bud. Both genes are also examples of genes whose functions are linked to formation of both the shoulder and distal limb elements. Furthermore, Alx4 expression is partly dependent on Gli3 function (see Fig. 1D,E) (see also Te Welscher et al., 2002), but the region of Alx4 downregulation in Gli3 mutants is not likely to be relevant for shoulder formation (e.g. Vargesson et al., 1997). Presumably Alx4-associated phenotypes, including radial/tibial dysplasia and polydactyly, relate to different aspects of its expression pattern, and it is possible that the expression that disappears in Gli3 mutants corresponds to the zeugopod and autopodal functions.

Defects of the clavicle

In contrast to the scapula, the clavicle arises through intramembranous rather than endochondral ossification. It evolved in primitive fish as a skeletal element at the base of the skull (see McGonnell et al., 1998), and, in mammals, is the only membranous bone outside of the skull. Alx4 and related genes have a function in shaping the neural crest-derived craniofacial skeleton, and we can therefore not exclude that the clavicle phenotypes we describe should be seen in that context. Nevertheless, a degree of redundancy can be seen between Tbx15 and Alx4/Cart1, even leading to complete suppression of the clavicle in the triple homozygous mutant. We therefore favor the notion that a similar disorganization locally in the shoulder girdle that also causes the scapular defect is the basis of the interference with clavicle formation.

Pax1 and Pax3 dysregulation in shoulder mutants

In the differentiating somite, the Pax1 gene is a sclerotomal marker. In the context of formation of the scapula, however, which is of dermomyotomal derivation, it is primarily considered to be a chondrocyte marker. Pax1 is linked to shoulder formation by the phenotype of undulated and other mutant alleles (Balling et al., 1988; Deutsch et al., 1988). Pax1 mutants lack part of the spine and the cartilaginous acromion. In addition, Pax1 is abnormally expressed in a number of shoulder mutants. Pellegrini showed that Pax1 was upregulated and shifted dorsally in Emx2 mutants that have totally lost the scapula (Pellegrini et al., 2001). By contrast, we demonstrate a downregulation and ventral shift of Pax1 expression associated with the scapula truncation in Alx4/Cart1 mutants, whereas loss of Gli3 or Tbx15 function leads to a similar downregulation, but without the ventral upregulation. Pax1 is inhibited by the application of beads containing BMP4 in chick limb buds, which is accompanied by scapula defects (Hofmann et al., 1998); however, it is induced by Sonic hedgehog (SHH) application (Laufer et al., 1994). At later stages, Shh is even upregulated in the anterior limb bud of Alx4 mutants (Chan et al., 1995). At E10.5, both Bmp4 and Shh were normally expressed in the limb regions of Alx4/Cart1 mutant embryos (data not shown). This suggests that these signaling pathways are not downstream of Alx4 and Cart1 in the mechanism leading to Pax1 deregulation in mutants. Intriguingly, Tbx15 and Pax1 have complementary rather than overlapping expression patterns (Fig. 1A,C), basically ruling out direct interaction. It should be noted that Tbx15, Alx4 (S.K., unpublished) and Cart1 (Ten Berge et al., 1998a) are not expressed in the dermomyotome, which is in contrast with the high dermomyotomal expression of Gli3 reported by McDermott and colleagues (McDermott et al., 2005). It therefore remains possible that Pax1 downregulation in Gli3 mutants is a direct consequence of interaction between these genes, but the effect on Pax1 expression seen in Alx4/Cart1 mutants suggests a model in which Pax1 deregulation reflects the disturbance of positional cues that guide cells destined to contribute to the shoulder. This would modify the view of Pax1 as a mere marker of cartilage/bone precursors, although the affected morphology of the acromion seen in most of the mutants studied here may be directly related to the loss of Pax1 in the acromioclavicular region where it is normally expressed. However, ectopic expression of Pax1 does not lead to ectopic cartilage elements, possibly due to a lack of permissiveness in its abnormal area of expression. Emx2 marks the prospective scapular blade region (Pellegrini et al., 2001; Pröls et al., 2004). The apparently normal Emx2 expression in all mutants studied shows that the altered Pax1 expression does not merely reflect the downregulation of markers for progenitors of structures that are affected.

Only recently has it fully emerged how genes specifically expressed in different somite compartments mark cells that migrate to the limb to form corresponding tissues. This process must depend on positional cues and its disruption is expected to be reflected in the expression of these markers. We therefore consider the shift in expression of Pax3, and to a lesser extent Scx, to support a model involving the disruption of positional signals, as suggested above. It should be noticed that the changes in expression of Pax1, Pax3 and Scx are seen in regions of embryos at a stage when anatomical or histological aberrations are not yet detectable, strongly suggesting that this dysregulation is a part of the mechanism that leads to the eventual skeletal defects. It remains to be seen whether it is the process of migration that is disturbed or whether some type of transformation or abnormal differentiation results in the shoulder malformations. The latter possibility is not supported.
by analyses of muscle tissue in Alx4/Cart1 mutants, as we noted only loss of muscle tissue, in particular affecting the supraspinatus muscle (not shown). *de* mutant embryos also have reduced muscle tissue (Curry, 1959; Singh et al., 2005). Huang et al. have suggested an essential causal link between the downregulation of *Pax3* in a subset of hypaxial dermomyotomes and the potential of this tissue to differentiate into cartilage (and to contribute to scapula or ilium) (Huang et al., 2000). In this respect, it is interesting that overexpression of the modulator of Wnt-signaling Carboxypeptidase Z in the dermomyotome of chick embryos leads to scapular defects, as well as ectopic *Pax3* expression (Moeller et al., 2003).

Results from grafting studies in chick embryos point to the importance of signals from the ectoderm to the underlying mesoderm, and the possible implication of FGF signaling (Ehehalt et al., 2004; Pröls et al., 2004). In *Alx4* mutants at E10.5, FGF4 is ectopically expressed in anterior limb bud ectoderm (Chan et al., 1995). Identifying the exact nature of the signaling cascade underlying scapula formation is a major challenge and may require combining genetics with the manipulation of embryon explants.

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