BMP action in skeletogenesis involves attenuation of retinoid signaling

Lisa M. Hoffman,1 Kamal Garcha,2 Konstantina Karamboulas,2 Matthew F. Cowan,2 Linsay M. Drysdale,1 William A. Horton,3 and T. Michael Underhill1,2

1Department of Physiology, Faculty of Medicine and Dentistry, University of Western Ontario, London, Ontario, Canada N6A 5C1
2Department of Cellular and Physiological Sciences, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z3
3Shriners Children’s Hospital, Portland, OR 97239

The bone morphogenetic protein (BMP) and growth and differentiation factor (GDF) signaling pathways have well-established and essential roles within the developing skeleton in coordinating the formation of cartilaginous anlagen. However, the identification of bona fide targets that underlie the action of these signaling molecules in chondrogenesis has remained elusive. We have identified the gene for the retinoic acid (RA) synthesis enzyme Aldh1a2 as a principal target of BMP signaling; prochondrogenic BMPs or GDFs lead to attenuation of Aldh1a2 expression and, consequently, to reduced activation of the retinoid signaling pathway. Consistent with this, antagonism of retinoid signaling phenocopies BMP4 action, whereas RA inhibits the chondrogenic stimulatory activity of BMP4. BMP4 also down-regulates Aldh1a2 expression in organ culture and, consistent with this, Aldh1a2 is actively excluded from the developing cartilage anlagen. Collectively, these findings provide novel insights into BMP action and demonstrate that BMP signaling governs the fate of prechondrogenic mesenchyme, at least in part, through regulation of retinoid signaling.

Introduction

Development of the vertebrate skeleton ensues with the aggregation of mesenchymal cells into condensations. In endochondral ossification, these precartilaginous condensations prefigure the elements of the adult skeleton, and alterations in this program lead to a range of congenital skeletal abnormalities. Various members of the transforming growth factor-β (TGF-β) family figure prominently at multiple stages within the skeletogenic program. Consequently, mutation or disruption of these genes or their receptors negatively impacts growth and development of the skeleton (Kingsley, 2001; Yoon et al., 2005). In particular, many of the bone morphogenetic proteins (BMPs) and growth and differentiation factors (GDFs) exhibit potent prochondrogenic activity. Indeed, several of the BMPs have been shown to stimulate ectopic cartilage formation both in vivo and in vitro, whereas disruption of Noggin, which is a BMP antagonist (of BMP2, -4, and, to a lesser extent, -7), leads to skeletal overgrowth (Brunet et al., 1998). Thus, it appears that BMPs may promote the expansion of cartilage, either by stimulating the proliferation of chondroprogenitors or chondroblasts, or by recruitment of cells with limited or no chondrogenic potential (Hall and Miyake, 2000). Downstream effectors of the BMP signaling cascade have been well characterized; however, the targets (direct and indirect) that underlie BMP action in chondrogenesis remain elusive.

Other signaling molecules that influence the chondrogenic program include vitamin A and its metabolites, the retinoids (Weston et al., 2003a,b). The retinoids act through the modulation of the transcriptional activity of the nuclear receptors for retinoic acid (RA), the RA receptors (RARs), and the retinoid X receptors. The transcriptional activity of these receptors is governed by RA availability, which is regulated largely by the combined actions of the enzymes involved in its synthesis and degradation, the ALDH1As and CYP26s, respectively. Indeed, the Rars, and other genes encoding enzymes involved in RA metabolism, are dynamically expressed during chondrogenesis. Furthermore, compound null mutants of the Rars and null mutants of Aldh2a1, Cyp26a1, or b1 present with a spectrum of skeletal abnormalities (Lohnes et al., 1994; Abu-Abed et al., 2001; Niederreither et al., 2002b; Weston et al., 2003b; Yashiro et al., 2004). The formation of precartilaginous condensations and the subsequent appearance of chondroblasts require the...
activity of Sox9, which is a transcription factor belonging to the Sry-related HMG box gene family (Bi et al., 1999; Akiyama et al., 2002). In accordance with a proposed role for RA signaling in chondrogenesis, RA influences the expression and/or activity of Sox9 (Weston et al., 2000, 2002).

In earlier studies, we demonstrated that mesenchymal cells isolated from a transgenic animal overexpressing a weak, constitutively active Rara transgene exhibit skeletal defects, and this, in part, results from delayed or inhibited chondroblast differentiation (Cash et al., 1997). Subsequent studies have indicated that the chondrogenic defect within the transgene mesenchyme is not rescued by the addition of BMP2 or -4, leading to the postulation that retinoid signaling may operate downstream of the BMP signaling pathway within this program (Cash et al., 1997; Weston et al., 2000). Further series of experiments demonstrated that skeletal progenitor differentiation requires RAR-mediated repression, and that antagonism of RAR signaling in primary cultures of limb mesenchyme is accompanied by increased Sox9 expression and activity (Weston et al., 2002). In this study, we demonstrate that Bmp4 decrease RA availability, and that this is required for their prochondrogenic function. Furthermore, during autopod development, Aldh1a2 expression is dynamically expressed and influenced by BMP signaling. During this process, Aldh1a2 expression becomes progressively restricted to nonchondrogenic regions, where it likely serves to inhibit or suppress expression of a chondroblast phenotype.

Results

To effectively model the chondrogenic program, we have used high-density primary cultures derived from the mesenchyme of embryonic age (E) 11.5 murine limb buds. For these purposes, two culture models have been used: (1) whole-limb (WL) cultures, which give rise to numerous cartilage nodules within 4 d (Fig. 1, A and B), and (2) distal tip (Tp) cultures, which contain a more homogenous chondrogenic progenitor population and, thus, produce a much greater number of cartilage nodules (Fig. 1 B; Gay and Kosher, 1984). Consistent with this, Tp cultures exhibit a higher level of Sox9 expression (not depicted) and increased basal SOX9 activity (Fig. 1 E), relative to WL cultures. In accordance with previous studies, the addition of BMP4 to either of these cultures results in an increase in cartilage formation both in WL and Tp cultures and in limb-bud organotypic cultures (Fig. 1, B and C). Accordingly, treatment with 10 ng/ml of exogenous BMP4 leads to a more than twofold increase in Sox9 expression in both Tp cultures and WL cultures (Fig. 1 D; not depicted). Moreover, the addition of BMP4 generates a dose-dependent increase in endogenous SOX9 activity, as measured with a SOX9-responsive reporter gene (Fig. 1 E).

Expression profiling of BMP action reveals the retinoid pathway as a central target

To better understand the mechanisms underlying BMP action, we used transcriptional profiling with Affymetrix U74 v2 chips A and B to identify genes in Tp cultures whose patterns of expression change in response to BMP4. Tp cultures were chosen for these analyses, as they are more homogenous and lack myogenic progenitors (Gay and Kosher, 1984; Weston et al., 2003c).

Initially, the array data was filtered to identify genes that exhibit at least a fourfold change in expression between any of the treatment groups, generating a list of 364 genes (Fig. 2 A). Further inspection of this group revealed that, with progressive culture time and/or the addition of BMP4, the expression of several cartilage ECM genes (Fig. 2, A and B, blue) and transcription factors with proscribed roles in chondrogenesis, such as Sox5, 6, and 9, and Dlx5 (Fig. 2, A and B; Smits et al., 2001; Robledo et al., 2002), increases significantly. Importantly, these trends in gene expression are consistent with expression of the chondroblast phenotype. To identify those genes that were specifically up- or down-regulated in response to BMP4, individual time points with and without treatment were analyzed and a stringent fourfold expression change cutoff was once again used. Genes from the 24- and 72-h time points were pooled, resulting in a list of 41 genes, 4 of which (Aldh1a2, Rbp1, Nog...
and Matn3) met the filtering conditions at both time points. Surprisingly, at 24 h, BMP2, -7, and GDF5 (Fig. 2 B, green) are down-regulated in response to BMP4, whereas Noggin expression increases approximately fivefold at this time point, as well as at the 72-h time point. Although BMPs have been shown to induce the expression of the inhibitory Smads, the expression of Smad6 and -7 appears unchanged over time and with BMP4 treatment (confirmed using Western blotting; unpublished data). However, it is particularly notable that multiple components of the retinoid signaling pathway are substantially down-regulated after BMP4 exposure. Indeed, Aldh1a2 and Cyp26a1, which are genes encoding enzymes involved in the synthesis and degradation of all-trans RA (atRA), respectively, exhibit the largest decreases at 24 h (14.8- and 7.3-fold, respectively). Interestingly, other RA synthesis enzymes, Aldh1a1 and Aldh1a3, are unaffected by BMP4 addition. The expression of retinol and RA-binding proteins, Rbp1 and Crabp2, and the RA-responsive receptor Rarb are also observed to be substantially decreased at 24 and 72 h after BMP addition. Thus, it appears that increased BMP4 signaling causes a wholesale reduction in the expression of multiple constituents of the retinoid signaling pathway.

Figure 2. Elucidation of the genetic programs underlying BMP action. (A) Expression profiling of BMP4-treated cultures reveals considerable changes in several gene families. Genes exhibiting a minimal fourfold change in expression between any of the time points or treatments were clustered using the GeneTraffic hierarchical clustering algorithm. Genes representative of the prominent clusters are shown to the right. Blue, red, and green colored genes represent ECM genes, retinoid signaling, and BMPs and their antagonists, respectively. (B) The dataset in A was filtered to identify those genes that exhibit a fourfold or greater difference in expression between untreated and the corresponding treated group. The same coloring scheme was applied as in A, and the boxed genes represent the four genes that exhibited a fourfold change in expression at both the 24- and 72-h time points.
RA status influences the expression of many of its binding proteins, receptors, and catabolism enzymes (de The et al., 1989; Durand et al., 1992; White et al., 1996). Thus, it is not entirely surprising that decreased expression of Aldh1a2 may lead to widespread changes in the expression of these genes. Consistent with this, changes in Aldh1a2 expression precede changes in the expression of these genes (unpublished data). For these reasons, we focused our attention on the analysis of Aldh1a2 expression in response to BMP4. Quantitative PCR confirmed that BMP4 addition reduces Aldh1a2 expression at 24 h (~12-fold reduction); further analysis revealed that Aldh1a2 expression is substantially reduced as early as 6 h (an approximately sixfold reduction), and at 12 h there is an ~38-fold differential between treated and untreated cultures (Fig. 3 A). As discussed earlier, BMP has the potential to recruit cells with low chondrogenic potential to the chondrocytic lineage. Based on this information, we sought to determine the distribution of Aldh1a2-expressing cells within limb mesenchymal cultures. Whole-mount in situ hybridization revealed that in WL cultures, Aldh1a2 is expressed in discrete foci in a pattern reminiscent of Col2a1 expression (Fig. 3 B). Furthermore, addition of BMP4 abolishes Aldh1a2 expression, whereas, consistent with previous observations, Col2a1 expression is intensified and its domain of expression expanded (Fig. 3 B). Thus, it appears that BMP4 expands cartilage formation through down-regulation of Aldh1a2.

BMPs function predominantly through modulation of Smad 1, 5, and 8 activity, and through activation of the p38 MAPK signaling pathway. To gain insights into the mechanisms underlying BMP regulation of Aldh1a2, a series of experiments were performed to address the requirement for protein synthesis and the role of mRNA stability in this process. 20 ng/ml BMP4 was added either shortly after culture initiation (2 h) or during the peak of Aldh1a2 expression (~18 h), and Aldh1a2 transcript abundance was quantified thereafter at 4 h intervals for 12 h. To determine if BMP4 decreased Aldh1a2 mRNA stability, BMP4-treated and untreated cultures were incubated with 5 μg/ml of the transcription inhibitor actinomycin D. In the presence of actinomycin D, Aldh1a2 mRNA levels decline in control cultures, and the presence of BMP4 does not accelerate this decline (Fig. 3 C).
In contrast, treatment of cultures with the protein synthesis inhibitor cycloheximide abolished down-regulation of Aldh1a2 by BMP4 (Fig. 3 C). There is an initial slight downward trend in the BMP4 and cycloheximide-treated cultures at the 4-h time point, but by 8 and 12 h there is no significant difference between the cycloheximide-treated control and BMP4 cultures. Thus, down-regulation of Aldh1a2 by BMP4 requires protein synthesis, indicating that BMP4 probably acts indirectly through the regulation of factors to down-regulate Aldh1a2.

**Endogenous RA signaling regulates expression of the chondroblast phenotype**

To further demonstrate the potential importance of ALDH1a2 in BMP4 action, we first examined the role of endogenous RA synthesis and degradation in chondrogenesis. Catabolic inactivation of RA is mediated by the CYP26 subfamily of cytochrome P450 enzymes (Niederreither et al., 2002a). Inhibition of RA degradation with an inhibitor of cytochrome P450 enzymes, ketoconazole (Osanai and Petkovich, 2005), leads to increased endogenous RA signaling, as evaluated with an RA-responsive reporter gene. Under these conditions, even small changes in endogenous RA availability (approximately fourfold) lead to a >10-fold reduction in SOX9 activity and a decrease in the formation of cartilage nodules (Fig. 4 A, insets). Importantly, the effects of ketoconazole on the retinoid and SOX9-responsive reporter genes can be completely reversed through addition of a pan-RAR antagonist, demonstrating that the observed effects of ketoconazole in this system reside in its ability to inhibit CYP26 enzyme activity (Fig. 4 B). Conversely, RA degradation increases through heterologous expression of Cyp26a1, and this is accompanied by a decrease in RA response element (RARE) reporter gene activity and an approximately fourfold increase in SOX9 activity (Fig. 4 C). Consistent with these observations, inhibition of ALDH1a2 activity with the ALDH1 inhibitor DEAB (Perz-Edwards et al., 2001) results in an approximately sevenfold reduction in “RA availability” and an approximately fivefold increase in SOX9 activity; this is associated with increased cartilage nodule formation (Fig. 4 D, insets). To follow Col2a1 expression in live cultures, WL cultures were established from transgenic embryos that contain a 6.3-kb portion of the Col2a1 promoter, driving expression of EGFP (Grant et al., 2000). In control cultures, weak transgene expression is apparent within 24 h, and by 96 h an abundance of EGFP-positive nodules can be observed (Fig. 4 E). Modulation of endogenous

![Figure 4. Modulation of endogenous retinoid signaling impacts SOX9 activity and cartilage formation.](image-url)
retinoid signaling via treatment with ketoconazole significantly impacts transgene expression, with fewer EGFP-positive cells being evident in these cultures. In contrast, attenuation of RA synthesis with DEAB leads to precocious and widespread transgene expression in comparison to control cultures (Fig. 4 E). Together, these results demonstrate that small changes in endogenous retinoid status profoundly influence expression of the chondroblast phenotype.

**BMP4 action is potentiated by and requires RAR-mediated repression**

We have previously shown in transgenic mice that cells expressing a weak, constitutively active Rara1 transgene present with skeletal abnormalities; of particular interest was the finding that transgene-expressing cells are generally absent from cartilages (Cash et al., 1997; Weston et al., 2000). Moreover, the addition of BMP2 or -4 fails to rescue the chondrogenic defect within the transgenic mesenchyme, leading to the postulation that the BMP signaling pathway operates upstream or in parallel to the retinoid signaling pathway within the chondrogenic program (Weston et al., 2000). To further delineate this relationship, we examined the ability of BMP4 signaling to modulate retinoid signaling directly. The addition of BMP4 to WL cultures leads to a dose-dependent decrease in RARE reporter gene activity, correlating with an increase in SOX9 activity (Fig. 5 A). In previous studies, we demonstrated that expression of the chondroblast phenotype relies on RAR-mediated repression (Weston et al., 2002). RAR-mediated repression involves recruitment of nuclear-corepressor complexes to target genes (Weston et al., 2003a). As such, we hypothesized that if BMP4 functions through the attenuation of retinoid signaling, then the chondrogenic-stimulatory

---

**Figure 5.** The prochondrogenic activity of BMP4 involves the attenuation of retinoid signaling and is enhanced by RAR-mediated gene repression. (A) Increasing concentrations of BMP4 (added at day 0) lead to a dose-dependent decrease in retinoid signaling (pGL3 [4X48]) and an increase in SOX9 activity (pGL3 [4X48]). (B) The ability of 10 ng/ml BMP4 to stimulate SOX9 activity (pGL3 [4X48]) and decrease retinoid signaling (RARE-luc) is enhanced by coexpression of Rara and/or its nuclear corepressor NCOR2. (C) Expression of the type I BMPRs (Bmpr1a or Bmpr1b) in the presence and absence of BMP4 also increases SOX9 activity and reduces retinoid signaling. (D and E) The addition of 100 nM atRA effectively neutralizes the stimulatory effect of BMP4 on both SOX9 activity (D) and cartilage formation (E). (F) Inhibition of atRA degradation by ketoconazole only partially interferes with BMP4-induced SOX9 activity. 10 ng/ml BMP4 was added at T = 0 (day 0; D0) and 2 μM ketoconazole was added at D0 or day 1 (D1). With the exception of B and C, in all experiments, cultures were treated 1 h after transfection; in B and C, cells were treated 24 h after transfection. Error bars represent the SD. **, P < 0.01; #, P < 0.001. Bar, 0.3 mm.
action of BMP4 will be potentiated by the presence of NCOR2 and/or RARα. Indeed, heterologous expression of Ncor2 or Ncor2 and Rara together increases SOX9 activity by ~2- and 10-fold, respectively. Treatment with BMP4 alone leads to a 3.6-fold increase in reporter gene activity, whereas treatment with BMP4 combined with expression of Ncor2 or Ncor2 and Rara increases reporter activity by 10- and 30-fold, respectively (Fig. 5 B). Importantly, SOX9 activity correlates inversely with the extent of the decrease in RARE reporter activity (Fig. 5 B). Consistent with our observations, overexpression of either of the BMP receptor (Bmpr) type I receptors, α or β, stimulates SOX9 activity, and this is associated with a reduction in RARE-luc activity (Fig. 5 C). These effects are potentiated by BMP4 addition. Together, these observations suggest that down-regulation of retinoid signaling in primary limb mesenchymal cells favors expression of a chondrogenic cell fate. Furthermore, addition of 100 nM atRA completely abrogates the prochondrogenic effects of BMP4 on the aforementioned reporter genes and on cartilage nodule formation (Fig. 5, C and D). Interestingly, treatment with ketoconazole on either day 0 or 1 of culture also inhibits the prochondrogenic action of BMP4 (Fig. 5 F), again indicating that even small changes in endogenous retinoid signaling affect expression of the chondrogenic phenotype.

Figure 6. BMPs and GDFs with prochondrogenic activity abrogate retinoid signaling. (A) The BMPs and GDFs increase cartilage formation to varying extents, as determined by staining of 4-d WL cultures with Alcian blue. (B) WL cultures transfected with reporter genes responsive to SOX9 activity [pGL3(4X48)] or retinoid signaling status [RARE-luc; pG5 + pBIND-RAR(DEF)], exhibit increased and decreased activity, respectively, to BMP2 (B2), 4 (B4), 6 (B6), and 7 (B7) and GDF5 (G5). All proteins were added at 10 ng/ml, with the exception of GDF5, which was added at 50 ng/ml; atRA and 310 were supplemented to a final concentration of 100 nM. (C) Aldh1a2 and Cyp26a1 expression is inversely proportional to SOX9 activity as determined by qPCR. (D) Antagonism of retinoid signaling phenocopies the effects of BMP4. WL cultures derived from Col2-transgenic mice were treated with vehicle, 20 ng/ml BMP4, or 100 nM of a pan-RAR antagonist (310). Note the more extensive network of EGFP-positive cells in the treated cultures. Images were collected 48 h after culture initiation. Error bars represent the SD. *, P < 0.05; #, P < 0.001. Bars: (A) 1 mm; (D) 0.25 mm.
Several of the BMPs and GDFs exhibit chondrogenic stimulatory activity; thus, we were interested in determining whether these factors also influence retinoid signaling. As illustrated in Fig. 6 A, the addition of BMP2, -4, -6, -7, or GDF5 stimulates chondrogenesis to varying extents. All of these factors are also expressed in the developing limb at various times during the formation of skeletal elements. Consistent with their effects on cartilage nodule formation, these ligands also exhibit a similar activity in their ability to increase SOX9 reporter gene expression (Fig. 6 B). Under these conditions, each factor also attenuates retinoid signaling, with BMP4 and GDF5 exhibiting the greatest negative effect (Fig. 6 B). Indeed, quantitative PCR further demonstrates that each factor decreases expression of both Aldh1a2 and Cyp26a1 (Fig. 6 C). The promoter of Cyp26a1 is retinoid-responsive (Loudig et al., 2000) and, thus, its decreased expression under these conditions provides further support that the presence of the aforementioned BMP/GDF abrogates retinoid signaling.

As indicated earlier, the addition of BMP4 leads to widespread cartilage formation both in vitro and in vivo. Enhanced cartilage formation after BMP4 treatment can also be observed within WL cultures derived from Col2-EGFP transgenic mice where BMP4 expression leads to widespread transgene expression. If BMPs operate, at least in part, through attenuation of retinoid signaling, then it would be expected that inhibition of retinoid signaling would phenocopy the action of BMPs. This is indeed the case; treatment of transgenic-derived WL cultures with either a pan-RAR antagonist or the ALDH1 inhibitor DEAB, albeit to a lesser extent, also leads to widespread transgene expression in a pattern reminiscent of BMP4 (Fig. 6 D). Collectively, these experiments suggest that the prochondrogenic activity of many of the BMPs and GDFs resides in their ability to abrogate expression of Aldh1a2, consequently resulting in the reduced activation of the retinoid signaling pathway.

**RA availability is regulated by BMP signaling in vitro and in vivo**

In the forelimb, the autopod cartilages, as determined by Col2a1 expression, first become evident around early E11, with the hindlimb following ~0.5 d later (Fig. 7 A). At the beginning of autopod development, Col2a1 expression in precartilaginous digital rays is quite weak, but quickly intensifies, such that by late E12 all the digits exhibit strong Col2a1 expression. In contrast, Aldh1a2 exhibits a dynamic pattern of expression that quickly changes from a band of expression through the early autopod to a fragmented appearance a few hours later (Fig. 7 A). Bifurcation of Aldh1a2 expression in the autopod occurs over a relatively short period of time (~9 h) and is closely associated with digit formation. As previously reported, Aldh1a2 expression appears between the developing zeugopod elements, within the regions flanking the digit cartilages, and within the interdigital region (IDR; Niederreither et al., 1997).

To assess the ability of BMP4 to regulate Aldh1a2 expression in limb buds, Affi-Gel blue beads soaked in either vehicle or 20 ng/μl BMP4 were implanted into the IDR region of late
E11 limb buds, followed by 24 h of organ culture. Implantation of BMP4-soaked beads into limb organ cultures stimulates ectopic Col2-EGFP expression (Fig. 7 B) and substantially modifies Aldh1a2 expression (Fig. 7 C). Consistent with the ability of BMP4 to stimulate ectopic cartilage in the early IDR as reported by others, BMP-soaked beads stimulated EGFP expression around the bead of all implanted limb buds \( (n = 10) \). EGFP expression was not detected around control beads \( (n = 8) \). Aldh1a2 was expressed to varying levels around control beads. In contrast, Aldh1a2 expression was excluded from those regions around the BMP4-soaked beads (Fig. 7 C). Together, these results demonstrate that BMP4 down-regulates the expression of Aldh1a2 in limb buds.

During early appendicular skeletal development, the BMPs, GDFs, and their receptors exhibit a complex pattern of expression, appearing at various times and locations within the cartilagenous anlagens. In this regard, activated BMP signaling has been observed in the developing cartilages, and an absence of the Bmpr1a and -1b severely compromises pre-cartilaginous condensation formation and chondroblast differentiation \((Yoon et al., 2005)\). Activation of either of these two receptors leads to a stage-dependent increase in cartilage formation \((Zou et al., 1997)\). In contrast, activated retinoid signaling inhibits chondrogenesis, whereas decreased retinoid signaling, either through antagonism of the receptors or in compound Rar knockouts, promotes chondrogenesis in vitro and in vivo \((Zou et al., 1997; Weston et al., 2003a,b)\).

Together, these observations would suggest that Aldh1a2 and liganded Rars should be excluded from developing cartilages. To examine the relationship of Aldh1a2-expressing cells and developing cartilages, double in situ hybridization was used in vitro and in vivo in WL cultures and E11.25–12.5 embryos, respectively. Aldh1a2 and Col2a1 are expressed in spatially distinct regions (Fig. 8, A and B). More specifically, Aldh1a2-expressing cells are excluded from Col2a1-expressing regions and from the apical ectodermal ridge and subjacent mesenchyme. During autopod development, small rays of Col2a1-expressing cells can be observed to bisect the band of Aldh1a2 expression (Fig. 8 A). Consistent with these observations, Aldh1a2-expressing cells are excluded from Col2a1-expressing regions in WL cultures. Furthermore, the distribution of Aldh1a2-positive cells would be expected to cause localized activation of the retinoid signaling pathway. This is, indeed, the case because establishment of WL cultures from a transgenic mouse harboring an RA-responsive reporter gene \((RARE-hsp68-lacZ; Rossant et al., 1991)\) demonstrates foci of transgene-expressing cells, which are distinct from the developing cartilages (Fig. 8 C). Transgene expression is markedly increased and decreased in response to 50 or 100 nM of exogenous atRA or the addition of 100 nM of 310, respectively (unpublished data). In both culture systems, BMP4 leads to expansion of Col2a1-expressing cells and increased cartilage formation, as well as substantial reduction in Aldh1a2 expression and RARE activity (Fig. 8 B, C). In aggregate, these findings suggest that during autopod development BMP signaling regulates expression of the chondrogenic phenotype by controlling RA availability.

### Discussion

Manipulation of either the BMP or the retinoid signaling pathway severely compromises skeletal ontogenesis. Although the mechanism of action of BMPs in chondrogenesis is poorly defined, previous studies have implied a potential connection between the BMP and RA pathways \((Weston et al., 2000)\). Using an unbiased genome-wide expression profiling strategy, we have defined the precise nature of this relationship and demonstrate, both in cell and organ culture, that BMP signaling controls RA availability by regulating Aldh1a2 expression. Furthermore,
unliganded Rars and RAR-mediated repression support expression of the chondrogenic phenotype. Thus, BMP signaling promotes chondrogenesis by enhancing RAR-mediated repression, which itself is regulated via attenuation of RA availability.

**Function of BMP signaling in chondrogenesis: involvement of the retinoid signaling pathway**

BMP2, -4 and -7, along with GDF5, bind and activate the BMPR type I a and b receptors. Several hallmarks of activated BMP/GDF signaling are observed in the developing skeleton, including the phosphorylation of Smads (1, 5, or 8; Brunet et al., 1998; Yoon et al., 2005). Noggin is also often up-regulated in response to the activation of BMPRIs (Canalis et al., 2003); this, too, was observed in this study (Fig. 2). An essential requirement for BMPRI-mediated signaling in endochondral ossification has been elegantly demonstrated by Yoon et al. (2005) through generation of compound null mutants of Bmpr1a and -1b. In this study, mutant animals were found to exhibit severe deficiencies in cartilage formation. More specifically, these animals present with poorly defined precartilaginous condensations that weakly express Sox9. Similarly, excess Noggin in vitro or in vivo leads to reduced cartilage formation, and decreased Sox9 expression and activity (Pizette and Niswander, 2000; Weston et al., 2000; unpublished data). Reduced activity of BMPs or GDFs through targeted or spontaneous mutations also negatively impacts the formation of precartilaginous condensations and subsequent cartilage formation. In contrast, expression of wild-type (Fig. 5 C) or constitutively active versions of the BMPR type I receptors promotes chondrogenesis (Zou et al., 1997; unpublished data).

Furthermore, ectopic BMP signaling in vivo and in vitro expands cartilage formation, likely through recruitment of cells not destined to become chondrocytes (Duprez et al., 1996a,b). Thus, BMP signaling appears to act at multiple stages within the chondrogenic program, including the establishment, maintenance, and differentiation of chondroprogenitors. The ability of BMPs to stimulate chondroblast differentiation is influenced by retinoid signaling (Figs. 4, 5, and 6), suggesting that at least a subset of these activities involves BMP-mediated attenuation of the retinoid signaling pathway.

Cells throughout the early autopod exhibit high chondrogenic potential, and these cells can be directed under a variety of conditions to form cartilage in vitro and in vivo (Lee et al., 1994; Ganan et al., 1996; Rodriguez-Leon et al., 1999). As autopod development ensues, the chondrogenic potential of many of these cells is lost, especially those within the IDRs, i.e., prechondrogenic mesenchyme loses its ability to become cartilage or is inhibited from doing so. In the presence of BMP signals, however, these cells express a chondrogenic fate (Fig. 7 A); this is especially apparent in the Noggin-null mice, which present with very broad digits and greatly limited IDR (Brunet et al., 1998). Importantly, during the establishment of these distinct regions, Aldh1a2 is dynamically expressed within these domains. Before overt chondrogenesis and robust expression of Col2a1, Aldh1a2 appears as a broad band throughout the autopod. As digit formation proceeds, Aldh1a2 expression is quickly extinguished in cartilage-forming regions, becoming localized to the nonchondrogenic flanking regions. At this embryonic stage, the developing limb is exquisitely sensitive to changes in retinoid status (Weston et al., 2003b), and the presence of Aldh1a2 is congruent with a role for retinoid signaling in inhibiting expression of the chondrogenic phenotype in cells flanking the developing digits. Moreover, activation of a RA-responsive reporter in transgenic cells is observed within the early IDR (Rossant et al., 1991), and RARE-expressing cells are excluded from developing cartilages (Fig. 8 C). In contrast, numerous studies have demonstrated that diminished retinoid signaling promotes chondrogenesis in vitro and in vivo (Weston et al., 2003a,b). In this study, we show that manipulation of endogenous RA production and signaling significantly impacts chondrogenesis (Figs. 4 and 5). In aggregate, these results suggest dual roles for the RARs in regulating chondrogenesis. Unliganded receptors promote expression of the chondroblastic phenotype, whereas liganded receptors inhibit differentiation of prechondrogenic cells. In this regard, local activation of the retinoid signaling pathway in the developing autopod would specify nonchondrogenic regions. Consequently, under conditions where retinoid signaling is diminished in the developing autopod, widened phalanges and/or cartilage formation in the IDR would be expected. Interestingly, Rara/g double-null mice present with both of these phenotypes. More specifically, a bulbous phalangeal abnormality is consistently observed, along with a less frequent appearance of ectopic cartilages in the IDRs (Lohnes et al., 1994). These mice also exhibit ectopic cartilage at several extraskeletal sites (Lohnes et al., 1994; Mendelsohn et al., 1994).

**Parallels in axial and appendicular skeletogenesis: overlapping players involving different mechanisms**

In the axial skeleton, BMPs play a role in the establishment and maintenance of an autoregulatory loop between the transcriptional repressor NKX3.2 and SOX9, thereby promoting axial chondrogenesis (Zeng et al., 2002). Interestingly, even though BMPs are sufficient and necessary for axial and appendicular chondrogenesis, their regulation of Sox9 appears to operate through an NKX3.2-independent manner in appendicular skeletogenesis (Zeng et al., 2002). In axial chondrogenesis, expression of a chondrogenic fate in somitic mesoderm appears to involve derepression of Sox9 by NKX3.2-mediated down-regulation of gene X, which is a transcriptional repressor of Sox9. Likewise, the retinoid pathway appears to be operating in a similar manner in the appendicular skeleton to regulate Sox9 and expression of a chondrogenic fate. In this scenario, activation of the retinoid signaling pathway up-regulates the expression of a negative regulator of Sox9 expression, gene Y, leading to decreased Sox9 expression and reduced cartilage formation. Conversely, antagonism of RAR-mediated signaling down-regulates the expression of Y, leading to derepression of Sox9 and increased cartilage formation, and, thus, supporting a chondrogenic-permissive condition. Thus, at least in the limb, BMPs function by attenuating the expression of Aldh1a2, thereby stimulating Sox9 expression and activity, and the elaboration of a chondroblastic phenotype. Both programs appear to converge
on negative regulators of Sox9, genes X and Y. Further complicating an understanding of BMP action in the limb is that BMPs do not appear to act directly to regulate Aldh1a2 expression, as protein synthesis is required for this activity. Thus, BMPs possibly act to increase the expression of a negative regulator of Aldh1a2 expression, or rather that BMPs may act directly through a relatively labile protein. Evidence for this latter scenario comes from the observation that in the absence of protein synthesis (Fig. 3C), BMP4 addition leads to an initial transient decrease in Aldh1a2 expression. Collectively, these findings demonstrate that BMP4-mediated establishment and maintenance of Sox9 expression in limb chondrogenesis involves a cascade of factors with the retinoid signaling pathway figuring prominently in this program. Further elucidation of the factors operating upstream and downstream of the RA signaling pathway will provide additional important insights into the molecular mechanisms underlying the chondrogenic program.

Materials and methods

Reagents
dRG, ketocanazole, diethyl amino benzaldehyde (DEAB), cycloheximide, and actinomycin-D were obtained from Sigma-Aldrich; all compounds were dissolved in 95% ethanol, with the exception of ketocanazole, which was dissolved in deionized water. BMPs and GDFs were purchased from R&D Systems and resuspended according to the manufacturer’s instructions. BMPs were added to media at a concentration of 10–20 ng/ml, whereas GDF5 was used at a concentration of 50 ng/ml to reflect its much lower activity (R&D Systems). AGN194310 was provided by R. Chandraratna (VitaE Pharmaceuticals, Irvine, CA).

Plasmid constructs

Reporter plasmids containing SOX9 binding sites (pGUS[4X48]) or trimerized RARE-luc were previously described (Weston et al., 2002). pG5, which is a reporter that contains five GAL4 binding domains, was obtained from Promega. To generate GAL4–RAR[DEF] fusions, the C-terminal region of Rara encompassing the ligand-binding domain was subcloned in-frame into pBlusDM (Promega). For expression in primary cells, full-length versions of murine Cyp26a1 (provided by M. Snead, University of California, Los Angeles, Los Angeles, CA) and Rara1 were subcloned into a modified pSG5 (Weston et al., 2002), and the construct containing an N-terminal EGFP fusion to full-length Ncor2 (provided by M. Privalsky, University of California, Davis, Davis, CA) was as previously described (Goodson et al., 2005). Mammalian expression plasmids containing Bmpr1a and Bmpr1b were provided by J. Wrana (University of Toronto, Toronto, Canada).

Establishment and transfection of primary mesenchymal cultures

Primary mesenchymal cultures from CD-1 E11.5 mouse limb buds were established as previously described (Weston et al., 2000) with the following modifications. For microarray analyses and other specified experiments, distal limb bud tips (subridge region) were dissected from E11.5 mouse embryos (the morning of the plug was considered E0.5) as described by Gay and Kosher (1984), with the excised region extending 0.3–0.4 mm from the distal apex of the limb to the proximal cut edge. After proteolytic digestion, cells were filtered through a cell strainer (40 μm) from the distal apex of the limb to the proximal cut edge. After proteolytic digestion, cells were filtered through a cell strainer (40 μm) and pelleted by centrifugation at 1000 × g. Cell pellets were washed three times with 5 ml PBS before being resuspended in 1 ml PBS. The cell suspension was plated into a 35-mm tissue culture dish (Nunc) and allowed to attach for 1 h and were subsequently processed for RNA isolation. For other cultures, the media was gently aspirated, and any remaining media was blotted from the well before the addition of the lys reagent. After isolation, the RNA was precipitated, and resuspended at 2 μg/ml; RNA quality was examined on a Bioanalyzer 2100 (Agilent), and RNA integrity number should not exceed the height of the membranes. Limbs were incubated under standard tissue culture conditions. After a 24-h incubation, EGFP expression was visualized using a dissection microscope (model MZ12; Leica) with epifluorescence. Limbs were subsequently fixed in 4% PFA before processing for whole-mount in situ hybridization.

Transcriptional profiling with microarrays: experimental design and analysis

RNA was harvested from primary cultures using RNAeasy (QIAGEN) according to the manufacturer’s instructions. For the zero time point, cells were allowed to attach for 1 h and were subsequently processed for RNA isolation. For other cultures, the media was gently aspirated, and any remaining media was blotted from the well before the addition of the lys reagent. After isolation, the RNA was precipitated, and resuspended at 2 μg/ml; RNA quality was examined on a Bioanalyzer 2100 (Agilent). For each time point, a minimum of two biological replicates were analyzed on U74V2 chips A and B. 10 μg of RNA was labeled and hybridized to the chips using the manufacturer’s recommended protocol.

Gene expression profiles were subsequently analyzed using MAS 5.0 (Affymetrix) and GeneTraffic UNO bioinformatics programs (Stratagene). All datasets were initially filtered to remove genes called absent by MAS 5.0, and were further filtered as indicated in the text using GeneTraffic. Hierarchical clustering was performed in GeneTraffic using gene clustering and a Pearson correlation distance metric.

Real-time PCR and whole-mount in situ hybridizations

To follow the expression of transcripts for Aldh1a2, Cyp26a1, Col2a1, and Sox9, quantitative real-time PCR was performed using the 7900HT Sequence Detection System (Applied Biosystems). Primers and MGB probes were designed using PrimerDesigner 2.0 (Applied Biosystems). The primer/probe sets used for detection of Sox9 and Col2a1 were as described in Weston et al. (2000) and the following primer/probe sets were used for quantifying Cyp26a1 transcript abundance: forward primer, 5′-CTACAACTGCAGCATCCTC3′; reverse primer, 5′-CGGCTGAAGGGCTGTACAT-3′; probe, 6FAM-5′-CTGGACAGTTGTCATG3′-MGBNFQ. Primer and probe concentrations were optimized according to the manufacturer’s instructions. Total RNA was isolated from primary cultures as described above. Quantification was performed using ~25 ng of total RNA and the expression of all genes relative to endogenous rRNA was determined using TaqMan Ribosomal Control Reagents (Applied Biosystems) and the comparative Cт method as described in User Bulletin #2 (Applied Biosystems).

Whole-mount in situ hybridization

Whole-mount in situ hybridization was performed on primary mesenchymal cultures as previously described (Weston et al., 2000) with the following modifications. After permeabilization using 10 μg/ml proteinase K in PBS supplemented with 0.05% Triton X-100, cells were postfixed in 4% PFA and 2% glutaraldehyde in PBS. Blocking and antibody incubations were performed in 1% blocking reagent (Roche) in 1× maleic acid buffer (100 mM maleic acid and 150 mM NaCl, pH 7.5). Riboprobes were synthesized in the presence of UTP-digoxigenin with the appropriate RNA polymerase and linearized template DNA, according to manufacturer’s instructions (Roche). Riboprobe complementary to Col2a1 was generated from BamHI-linearized plasmid containing 1.1 kb of the C-propeptide–encoding region of Col2, and transcribed in vitro with 17 RNA polymerase. Aldh1a2 riboprobe was transcribed from EcoRI-linearized and modified plasmid containing a 400-bp fragment of the Aldh1a2 coding sequence.
using T3 RNA polymerase. Double in situ hybridizations were performed as above, but with the following modifications. Hybridization was performed using both DIG- and fluorescein-labeled RNA probes. Cultures were subsequently incubated overnight in fluorescein-labeled antibody (for detection of Aldh1a2). After incubation in NBT/BCIP/10% PVA–staining buffer, cultures were rinsed twice with PBS, and then fixed for 10 h in a 4% PFA/PBS solution. Cultures were again briefly rinsed twice in PBS, and the blocking antibody and staining steps were repeated, using an anti-DIG-AP antibody and INT/BCIP for detection of Col2a1.

Single and double whole-mount in situ hybridization on limb buds and cultured limbs was performed as described by Hargrave and Koopman (2000). Double in situ hybridizations were performed as described in the previous paragraph, except that BCIP alone was used for detection of Col2a1. To enhance visualization of the light blue (BCIP) and purple staining (NBT/BCIP), all images were adjusted to maximum hue in Photoshop (Adobe).

Microscopy and image acquisition

Images of fixed cultures in 70% ethanol or Tris-buffered salt solution with 0.1% Triton X-100 (TBST) were collected at room temperature using either a dissecting microscope (Stemi SV11 Apo, S1.6× objective; Carl Zeiss MicroImaging, Inc.) or an inverted microscope (Axiovert S100; Carl Zeiss MicroImaging, Inc.) fitted with a PC-Achromat 5×, 0.12 NA, PC-Achromat 10×, 0.25 NA, LD Achromatgmat, 0.55 NA, 10× Fluor, 0.5 NA, and an LD Achromplan 40×, 0.6 NA. Monochromatic and color images were acquired from a QImaging Retiga Exi 12-bit camera and a QImaging Retiga 1300i (12-bit) camera, respectively, using OpenLab 4 software (Improvision). Live cell and organ culture images were collected at room temperature in culture media with either an Axiovert S100 microscope or a dissection microscope (MZ FLII, Plan 1.0× objective; Leica). Photoshop was used to adjust some image levels.

Statistical analysis

All luciferase assays were performed in quadruplicate and repeated using three distinct preparations of primary cells. Real-time PCR analysis was performed in duplicate and repeated a minimum of two times with independent RNA samples. Real-time PCR and luciferase reporter data were analyzed by one-way analysis of variance, followed by a Bonferroni post-hoc test for multiple comparisons using GraphPad Prism, Version 4.0 (GraphPad Software, Inc.). Significance is represented as follows: * P < 0.05; ** P < 0.01; # P < 0.001. One representative experiment is shown for all luciferase and real-time PCR results.

We would like to thank Rosh Chandraratna for providing us with the pan-RAR antagonist, AGN 194310. Also, we thank Martin Privalsky for an expression plasmid of Ncor2 (Novartis KG), from which Ncor2 was amplified and cloned into a modified pCMV-Tag vector, with an N-terminal glutathione S-transferase (GST) fusion for enhanced solubility in E. coli. Transient transfection experiments were performed in duplicate and repeated a minimum of two times with independent RNA samples. Real-time PCR and luciferase reporter data were analyzed by one-way analysis of variance, followed by a Bonferroni post-hoc test for multiple comparisons using GraphPad Prism, Version 4.0 (GraphPad Software, Inc.). Significance is represented as follows: * P < 0.05; ** P < 0.01; # P < 0.001. One representative experiment is shown for all luciferase and real-time PCR results.


