Retinoic acid stimulates myocardial expansion by induction of hepatic erythropoietin which activates epicardial Igf2

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SUMMARY
Epicardial signaling and Rxra are required for expansion of the ventricular myocardial compact zone. Here, we examine Raldh2+/− and Rxra−/− mouse embryos to investigate the role of retinoic acid (RA) signaling in this developmental process. The heart phenotypes of Raldh2 and Rxra mutants are very similar and are characterized by a prominent defect in ventricular compact zone growth. Although RA activity is completely lost in Raldh2+/− epicardium and the adjacent myocardium, RA activity is not lost in Rxra+/− hearts, suggesting that RA signaling in the epicardium/myocardium is not required for myocardial compact zone formation. We explored the possibility that RA-mediated target gene transcription in non-cardiac tissues is required for this process. We found that hepatic expression of erythropoietin (EPO), a secreted factor implicated in myocardial expansion, is dependent on both Raldh2 and Rxra. Chromatin immunoprecipitation studies support Epo as a direct target of RA signaling in embryonic liver. Treatment of an epicardial cell line with EPO, but not RA, upregulates Igf2. Furthermore, both Raldh2+/− and Rxra+/− hearts exhibit downregulation of Igf2 mRNA in the epicardium. EPO treatment of cultured Raldh2+/− hearts restores epicardial Igf2 expression and rescues ventricular cardiomyocyte proliferation. We propose a new model for the mechanism of RA-mediated myocardial expansion in which RA directly induces hepatic Epo resulting in activation of epicardial Igf2 that stimulates compact zone growth. This RA-EPO-Igf2 signaling axis coordinates liver hematopoiesis with heart development.

KEY WORDS: Retinoic acid, Erythropoietin, Heart development, Epicardium, Myocardial compact zone, Liver, Raldh2, Epo, Igf2, Mouse

INTRODUCTION
Retinoic acid (RA) synthesis is catalyzed by three retinaldehyde dehydrogenases (RALDHs) encoded by Raldh1, Raldh2 and Raldh3 (Aldh1a1, Aldh1a2 and Aldh1a3, respectively – Mouse Genome Informatics), with RALDH2 being the main enzyme providing RA for early organogenesis (Duester, 2008). As expression of these enzymes is restricted in a temporal and spatial manner, RA synthesis is a major point of control for the RA signaling pathway. RA binds to nuclear retinoic acid receptors (RARα, RARβ and RARγ) which form heterodimers with retinoid X receptors (RXRα, RXRβ and RXRγ) to regulate the transcription of target genes (Kastner et al., 1995; Mangelsdorf and Evans, 1995; Niederreither and Dolle, 2008). Binding of a retinoid ligand to one of the RXRs appears to be unnecessary for RA signaling (Mic et al., 2003; Calleja et al., 2006), and it remains unclear whether physiological ligands exist for RXR (Mascrez et al., 2009). Expression of the six RAR and RXR genes is very broad, resulting in redundant functions, illustrated by the fact that among all six mutants only Rxra−/− mice exhibit an embryonic lethal phenotype (Mark et al., 2009).

RA signaling is a key factor in heart development. This was first demonstrated by depriving rat and avian embryos of dietary vitamin A, resulting in a vitamin A deficiency syndrome characterized by defects in many organs, including the heart, which exhibits abnormal early development and a thinning of the ventricular myocardium (Wilson et al., 1953; Dersch and Zile, 1993; Zile, 2001). Genetic loss-of-function studies have demonstrated that Rxra−/− embryos exhibit ventricular myocardial thinning (Kastner et al., 1994; Sucov et al., 1994), whereas Raldh2+/− embryos exhibit an early heart defect (Niederreither et al., 2001). Recent studies using Raldh2+/− embryos demonstrated that RA limits the size of the second heart field population along the anteroposterior axis by negatively regulating cardiac Fgf8 (required for expression of Isil), thus defining the posterior boundary of the heart field (Rycebusch et al., 2008; Sirbu et al., 2008). Also, loss of radlh2 (aldh1a2 – Zebrafish Information Network) function in zebrafish increases the heart progenitor population (Keegan et al., 2005). The mechanism through which RA regulates expansion of the ventricular myocardium is unknown. After the four-chambered heart has formed, the naked myocardium is covered from embryonic day (E)9.5-10.5 by the epicardium, an epithelial cell layer derived from the proepicardial organ that originates from the septum transversum mesenchyme (Komiyama et al., 1987; Mannar et al., 2001). Some epicardial cells undergo an epithelial-to-mesenchymal transition in response to signals from the ventricular myocardium (Snarr et al., 2008). These epicardial-derived cells create the subepicardial mesenchyme and differentiate further into smooth muscle cells of the coronary vessels and cardiac fibroblasts (Lie-Venema et al., 2007). Signals from the endocardium and the epicardium ensure normal maturation of the myocardium in subsequent developmental stages, with the endocardium primarily governing the development of the trabecular myocardium, and the epicardium being an important source of mitogens for compact zone myocardium (Smith and Bader, 2007; Lavine and Ornitz, 2008). This instructive role of the epicardium is emphasized by the...
fact that mouse mutants displaying impaired epicardial development have an underdeveloped compact zone myocardium (Kwee et al., 1995; Yang et al., 1995). Data from chicken embryos, in which the formation of the epicardium has been disrupted mechanically, show that ventricular regions devoid of the epicardium do not undergo myocardial expansion (Manner, 1993; Gittenberger-de Groot et al., 2000). Mouse Rxra−/− embryos fail to expand the ventricular myocardial compact zone (Kastner et al., 1994; Sucov et al., 1994), but Rxra function in cardiomyocytes is not required (Chen et al., 1998; Subbarayan et al., 2000). Conditional Rxra−/− embryos, obtained using a Gata5-Cre expressed in epicardium and other derivatives of the septum transversum, exhibit thinning of the myocardial compact zone, suggesting that RXRα might function in the epicardium to induce secretion of a myocardial proliferative factor (Merki et al., 2005). However, RA has never been linked directly to epicardial function, and the factor secreted by the epicardium that stimulates myocardial expansion has remained elusive.

Several growth factors have been suggested to function in communication between the epicardium and myocardium. Conditional deletion of Rxra and β-catenin in epicardial and septum transversum mesenchyme derivatives using Gata5-Cre suggested a WNT connection, but direct evidence for the cooperation of RA and WNT signaling pathways during myocardial expansion has not been reported (Merki et al., 2005; Zamora et al., 2007). Another study showed that Fgf9 is required for myocardial development and that cardiac Fgf9 expression can be induced by pharmacological RA doses in heart organ cultures; however, as Fgf9 is expressed primarily in the endocardium and not expressed in the epicardium after E10.5, it seems unlikely that FGF9 signaling alone can induce compact zone proliferation (Lavine et al., 2005). Another protein implicated in ventricular compact zone growth is erythropoietin (EPO) as demonstrated by similar myocardial defects in null mutant mice for Epo (expressed in the liver but not heart) and Epor (encoding the EPO receptor; expressed in epicardium and endocardium, as well as liver) (Wu et al., 1999). Interestingly, Epo expression in embryonic liver is greatly reduced in Rxra−/− embryos (Makita et al., 2001).

In this study, we focused on how RA signaling influences the epicardial/myocardial signaling needed for myocardial compact zone development. Although Raldh2−/− embryos normally die at E9.5, we show that Raldh2−/− embryos rescued with a small dose of RA prior to E9.5 survive to later stages, similar to Rxra−/− embryos, and exhibit a severe heart defect characterized by a thin compact zone myocardium. Surprisingly, although Raldh2−/− embryos lose cardiac RA activity, Rxra−/− embryos retain normal cardiac RA activity, suggesting that an RA signaling event outside the heart is responsible for the ventricular phenotype. We demonstrate that the RA target gene Epo is downregulated in hepatic tissues of both Raldh2−/− and Rxra−/− embryos, and that EPO function is necessary for epicardial induction of insulin-like growth factor-2 (IGF2). We propose a new mechanism for compact zone maturation in which EPO, induced by hepatic RA signaling, travels to the epicardium and induces IGF2, which is secreted by the epicardium to stimulate myocardial compact zone development.

MATERIALS AND METHODS

Transgenic mice

Generation of Raldh2 null embryos and Raldh2 null embryos carrying the RARE-lacZ reporter transgene were described previously (Mic et al., 2002). Germline Rxra null embryos were obtained from mice carrying a floxed Rxra gene (Chen et al., 1998) crossed with mice that express Cre recombinase under the control of the protamine promoter, which enables homologous recombination in the male germline (O’Gorman et al., 1997). Conditional Rxra null mutants were obtained by crossing Rxra floxed mice with a line expressing Cre recombinase under the control of the chicken Gata5 promoter (Merki et al., 2005). Genotyping of embryos was performed by PCR analysis of yolk sac DNA. All mouse studies were performed according to regulatory standards adopted by the Animal Research Committee at the Sanford-Burnham Medical Research Institute.

Dietary rescue of Raldh2 null mutants

The protocol for rescue of Raldh2−/− lethality by dietary supply of RA to a pregnant dam was described previously (Zhao et al., 2010). Briefly, a 50 mg/ml stock solution of all-trans-RA (Sigma) in 100% ethanol was mixed with corn oil to obtain a 5 mg/ml RA solution, which was mixed thoroughly with ground mouse chow to yield 0.1 mg RA/g mouse chow. RA-supplemented food was provided from E6.75 to E9.25 and was changed every 12 hours to ensure activity. At E9.25 mice were returned to normal food until collection of embryos at E10.5-E13.5. This low dose of RA provides a physiological amount of RA (Mic et al., 2003) and is cleared within 12-24 hours of the end of treatment at E9.25 (Mic et al., 2002), thus allowing analysis of embryos from E10.5 onwards that are RA-deficient.

Whole-mount and section in situ hybridization, immunohistochemistry and histology

In situ hybridization of whole-mount hearts or paraffin-embedded heart sections (5 μm) was performed as described (Wilkinson and Nieto, 1993). Staining of wild-type and mutant samples was performed for an equal length of time and experiments were repeated at least three times. For whole-mount hearts, sectioning was performed with a vibrotome after staining; tissues were embedded in gelatin-bovine serum albumin (BSA) solution (0.5% gelatin, 30% BSA, 20% sucrose in PBS, polymerized by addition of 50% glutaraldehyde) and sectioned at 20 μm. The riboprobes used for this study included Raldh2 (Mic et al., 2002), Tbx18 (Kraus et al., 2001) and Igf2 (generated here by RT-PCR). Immunohistochemistry on paraffin sections was performed as previously described using an affinity-purified anti-RALDH2 antibody at 1:200 (Haselbeck et al., 1999), anti-MF20 (Developmental Studies Hybridoma Bank; 1:20) and anti-Ki67 (Sigma Chemical; 1:100). For histological analysis, paraffin sections were stained with Hematoxylin and Eosin. RARE-lacZ transgenic mice and β-galactosidase staining have been described previously (Rossant et al., 2001); hearts were dissected from embryos, stained for the same length of time and vibratome sectioned as described above.

Semi-quantitative RT-PCR

RNA was isolated from frozen specimens using Trizol (Invitrogen) according to the manufacturer’s guidelines. Equal amounts of RNA were used to synthesize cDNA using Superscript III reverse transcriptase (Invitrogen) and standard protocols, and 1 μl cDNA was used for subsequent PCR reactions. The following primer sets were used to amplify cDNA fragments: GAPDH: Gapdh f: CAGCTTCGCGCACAGATTCA, Gapdh r: GACACCTGACTTCTCTGTC; EPO: EPO f: CCMCCCTGCTGTGTATTTACTC, EPO r: CCGTGTGGACCGTGATACCCCT; FGF-9: Fgf_9_f: TGGACACCGGAAGGATAC, FGF_9_r: CCGAGCTGTGGGAAGCTGCTTCT; EPO_r: CCTCTCCCGT GTACAG - . The following PCR program was used for amplification: 95°C for 2 minutes; 95°C for 30 seconds; 60°C for 30 seconds; 72°C for 45 seconds; 72°C for 5 minutes; 30 cycles in total for all genes analyzed.

Chromatin immunoprecipitation

Chromatin immunoprecipitation (ChIP) was performed according to the manufacturer’s ChIP protocol (Active Motif, Carlsbad, CA, USA). Five livers from E13.5 wild-type mouse embryos were dissected and cross-linked with 1% formaldehyde at room temperature for 15 minutes. Isolated nuclei (in 650 μl) were sonicated on ice for 20 pulses of 10 seconds each at 40% power output using a microtip probe from a Misonix Digital Sonicator 4000 (Cole-Parmer Instrument Company, Vernon Hills, IL, USA) to shear the DNA to an average size of 500 bp followed by centrifugation.
at 13,000 g for 10 minutes. At this point, a small portion of supernatant was stored as the input control. For each ChIP reaction, immunoprecipitation was performed using 150 μl of sheared chromatin mix with 3 μg of either anti-RAR-α (sc-551, Santa Cruz Biotechnology), anti-RAR-β (Affinity Bioreagents), anti-RAR-γ (sc-550, Santa Cruz Biotechnology) or control IgG, along with 25 μl pre-blocked protein G-coated magnetic beads (Active Motifs, Carlsbad, CA, USA) for 4 hours at 4°C. Beads were washed and eluted DNA-protein complexes were reverse cross-linked and purified. The immunoprecipitated DNA was analyzed by PCR, and was compared with input DNA that was diluted 100-fold. For each antibody, ChIP analysis was performed in at least two independent experiments. PCR products were verified with 3% agarose gel electrophoresis. RARE specific and non-specific primer sequences for mouse erythropoietin gene used in this study were as follows: Epo-RARE-Fwd: CAGCTGAAATCACCAC-ACCAGACTC; Epo-RARE-Rev: CTCTGACTGCTCCGTGTCTTC; Epo-NS-Fwd: GCAATGAGCATGACTTACGTG; Epo-NS-Rev: CTGTTGCGCTCCTCAGCATCA.

**Culture of epicardial cells**
Mouse epicardial cells (MEC1) were grown in DMEM supplemented with 10% fetal bovine serum until 80% confluence was reached, then were switched to serum-free DMEM for 24 hours. The media was then replaced with fresh DMEM including all-trans-RA (1 μM; Sigma) or recombinant mouse EPO (10 ng/ml; R&D Systems) for 24 hours. RNA was isolated using Trizol (Invitrogen) following the manufacturer’s instructions. cDNA was synthesized from equal amounts of total RNA with the iScript cDNA Synthesis Kit (Bio-Rad). Real-time PCR analysis was performed using iQ SYBR Green Supermix (Bio-Rad) with an Opticon2 thermocycler (MJ Research). A standard curve was performed with serial dilutions of cDNA. Experiments were run in duplicate and expression levels were analyzed using Opticon Monitor Analysis Software and normalized against β-actin expression levels. The following primer sequences were used to amplify cDNA fragments: Igf2_f: CCCTCAGCAATGCGCTTAAG; Igf2_r: TTAGGGTGCCCTCAGATGTT; β-actin_f: ATGGAGGGGGAATACAGCCC; β-actin_r: TTCTTTGAGCCTCCTCCTT.

**Heart organ culture**
Hearts were dissected at E11.5, cultured overnight at 37°C in 5% CO₂ for 18 hours in 6-well plate transwell inserts (Millipore) in serum-free medium consisting of DMEM F12/Glutamax (Gibco) supplemented with 2 μg/ml heparin and, where indicated, with 8 U/ml of human recombinant erythropoietin (Calbiochem). Hearts were fixed overnight in 4% paraformaldehyde in PBS, paraffin sectioned at 5 μm and subjected to in situ hybridization or immunohistochemistry (see above). Quantification of proliferating cardiomyocytes was performed by two researchers independently using ImageJ software. Percentages of proliferating cardiomyocytes for each genotype were plotted and statistical analysis using t-test was carried out using GraphPad Prism software.

**RESULTS**

**Cardiac phenotypes of rescued Raldh2+/− mutants and Rxra−/− mutants**
A distinct growth phase of the compact zone myocardium begins at E10.5, after the formation of the epicardium is completed, and by E11.5 the compact myocardium becomes morphologically recognizable (Smith and Bader, 2007). At E13.5, wild-type hearts exhibited a well-developed ventricular compact zone myocardium (Fig. 1A,D), whereas Rxra−/− hearts displayed a thin compact zone myocardium (Fig. 1B,E) as reported previously (Kastner et al., 1994; Sucov et al., 1994). As Rxra−/− myocardial defects might be due to defective RA signaling, we examined Raldh2+/− embryos, which exhibit loss of RA synthesis. Raldh2+/− embryos display early embryonic lethality at E−9.5, but low-dose RA treatment from E6.75 to E9.25 delays lethality, allowing analysis of E13.5 Raldh2+/− embryos that lack RA activity in tissues where RALDH2 is the source of RA (Zhao et al., 2010). Rescued Raldh2+/− embryos exhibited a very similar heart morphology at E13.5 compared to Rxra−/− embryos, characterized by a thin underdeveloped ventricular compact zone (Fig. 1C,F). This striking similarity in phenotypes suggests that a common RA signaling event stimulating compact zone growth has been affected in both mutants.

**Cardiac RA signaling activity is lost in Raldh2 mutants but not in Rxra mutants**
In order to determine whether the underdeveloped ventricular myocardial compact zone observed in Raldh2+/− and Rxra−/− embryos is associated with a loss of epicardial RA signaling, we examined cardiac RA signaling using embryos carrying the RARE-lacZ RA-reporter transgene (Rossant et al., 1991). In E10.5 wild-type hearts, RA signaling was evident in the atria and the outflow tract but was either absent or detected at very low levels in the ventricle (Fig. 2A); vibratome sections revealed little or no detection of RA activity in the ventricular epicardium at E10.5 (Fig. 2D). Rxra−/− hearts exhibited no difference in cardiac RARE-lacZ expression at E10.5 compared with wild type (Fig. 2B,E). By contrast, RARE-lacZ expression in E10.5 rescued Raldh2+/− hearts was nearly eliminated (Fig. 2C,F). In E12.5 wild-type hearts, RA signaling activity was detected in clusters of cells throughout the ventricular epicardium, whereas in the atria lower levels of RA activity were observed compared with E10.5 hearts (Fig. 2G,J). Surprisingly, E12.5 Rxra−/− hearts exhibited no significant reduction in RA signaling activity in the ventricular epicardium (Fig. 2H,K) compared with E12.5 rescued Raldh2+/− hearts, which completely lacked RA activity in the ventricular epicardium (Fig. 2L). These findings suggest that the compact zone defect in Rxra−/− hearts is not due to a loss of epicardial RA signaling.

As epicardial RA signaling activity was not observed in rescued Raldh2+/− hearts, we determined whether the epicardium develops in these mutants by analyzing the expression of Tbx18, which is a
marker for the proepicardial organ and the epicardium (Bussen et al., 2004). At E9.5, unrescued Raldh2–/– embryos exhibited a proepicardial organ marked by Tbx18 expression, demonstrating that formation of this tissue can occur in the absence of Raldh2 function (Fig. 3A–D). Analysis of E10.5 Raldh2–/– embryos (rescued to avoid lethality) revealed that Tbx18 mRNA was expressed in the epicardium at a level similar to that observed in wild type (Fig. 3E,F). Thus, the loss of RA activity observed in rescued Raldh2–/– hearts is not due to a failure to generate the epicardium.

The late appearance of RA activity in the ventricular epicardium (E12.5) is inconsistent with a role for epicardial RA in compact zone formation, which initiates at ~E10.5 (Smith and Bader, 2007). Previous studies have demonstrated that detection of RALDH2 protein in the ventricular epicardium is not observed until E12.5 (Moss et al., 1998), consistent with our observations of RA activity in this tissue (Fig. 2A,G). We further examined whether epicardial Raldh2 expression appears late after epicardium formation. We found that Raldh2 mRNA was not detectable in cardiac tissues at E9.5, but was observed in the adjacent splanchnic mesoderm (see Fig. S1A-B in the supplementary material). At E10.5, after epicardial formation has completed, Raldh2 mRNA was still not observed in the epicardium (see Fig. S1C-E in the supplementary material).

Also, immunohistochemical staining did not detect RALDH2 protein in the heart at E10.5 (see Fig. S1F,G in the supplementary material). At E12.5, RALDH2 protein was detected in the epicardium, pericardium, diaphragm and liver mesothelium (see Fig. S1H-K in the supplementary material). Our findings thus demonstrate that epicardial RA synthesis by RALDH2 initiates between E11.5 and E12.5. A cell-autonomous role for RA in the ventricular epicardium at E10.5 has been proposed to regulate the expression of a secreted factor that in turn induces cardiomyocyte proliferation and compact zone development (Lavine et al., 2005). However, our analysis of Raldh2 mRNA and protein expression as well as detection of RA signaling using RARE-lacZ does not support this hypothesis. Moreover, we now demonstrate that RA signaling observed in the ventricular epicardium at E12.5 does not require Rxra. Normal RA activity in Rxra–/– hearts might be due to the redundant nuclear receptor RXRβ, which is also expressed in heart (Wendling et al., 1999), but loss of Rxra function alone impairs compact zone growth (Kastner et al., 1994; Sucov et al., 1994). Taken together, these findings implicate an RA signaling event outside the heart, requiring both Raldh2 and Rxra, that controls ventricular compact zone expansion.
Analysis of Epo expression in hepatic and ventricular tissues

Epicardial development and liver organogenesis are intricately linked as it has been shown that endodermally derived hepatoblasts migrate into the septum transversum mesenchyme to form a liver bud surrounded by coelomic mesothelium (Zorn and Wells, 2009), and the septum transversum mesenchyme also gives rise to the proepicardial organ and epicardium (Komiyama et al., 1987). RALDH2 is detected in the liver mesothelium at E10.5-E13.5 (Ijpenberg et al., 2007). We also detected RALDH2 immunoreactivity in the liver mesothelium at E12.5 (see Fig. S1J,K in the supplementary material). It has been demonstrated previously that RXRα and RA synthesis is necessary for normal liver development. Rxra–/– embryos (Makita et al., 2001) and rescued Raldh2+/- embryos (Wang et al., 2006) both exhibit variable reductions in liver size. Also, previous studies on Wt1+/- and Rxra–/– mouse embryos and analysis of chick embryos treated with RA synthesis inhibitors have demonstrated that RA/RXRα signaling functions downstream of Wt1 in liver mesothelium, and that loss of RA signaling disrupts development of the liver mesothelium leading to reduced progenitors for hepatic stellate cells (Ijpenberg et al., 2007), which are known to secrete EPO (Maxwell et al., 1994). Additionally, there is evidence that expression of EPO in hepatic tissues is regulated by RA, as shown in Rxra–/– embryos that exhibit a large reduction in hepatic Epo expression (Makita et al., 2001). Furthermore, Epo+/- and Epor–/– embryos exhibit growth arrest of the ventricular compact zone myocardium, consistent with the observed expression of Epor in the epicardium and endocardium (Wu et al., 1999). As our findings above suggest that an RA signaling event outside the heart is responsible for induction of an epicardial mitogen, we further examined the expression of Epo in liver.

We analyzed Epo mRNA levels in hepatic and cardiac tissues of Rxra–/– and rescued Raldh2+/- embryos. We also examined a conditional Rxra–/– model using a Gata5-Cre that is expressed in the epicardium as well as other derivatives of the septum transversum mesenchyme, including the liver coelomic mesothelium (Merki et al., 2005). The morphological heart phenotype of Gata5-Cre:Rxra–/– conditional mutants recapitulates that observed in germline Rxra–/– and rescued Raldh2+/- embryos (Merki et al., 2005). A semi-quantitative RT-PCR approach was used to analyze expression of Epo in hepatic and ventricular tissues from wild-type and mutant embryos at E11.5 and E12.5. We found that Epo mRNA was significantly downregulated in hepatic tissues at E11.5 and E12.5. No change was observed in ventricular tissues; as a control, rescued Raldh2+/- embryos exhibit a loss of Raldh2 mRNA. Epo mRNA is also reduced in livers from germline Rxra–/– embryos and Gata5-Cre x Rxra–/– conditional mutant embryos. Expression of Fgf9 mRNA is not altered in any of the analyzed tissues and mutants relative to wild type. GAPDH, glyceraldehyde 3-phosphate dehydrogenase mRNA control.

![Fig. 4. Analysis of Epo and Fgf9 expression in hepatic and ventricular mouse tissues.](image)

Semi-quantitative RT-PCR shows that Epo mRNA is reduced in the liver of rescued Raldh2+/- embryos at E11.5 and E12.5 relative to wild type, whereas Epo expression is not detectable in ventricular tissues; as a control, rescued Raldh2+/- embryos exhibit a loss of Raldh2 mRNA. Epo mRNA is also reduced in livers from germline Rxra–/– embryos and Gata5-Cre x Rxra–/– conditional mutant embryos. Expression of Fgf9 mRNA is not altered in any of the analyzed tissues and mutants relative to wild type. GAPDH, glyceraldehyde 3-phosphate dehydrogenase mRNA control.

Epo is a direct target of RA signaling in embryonic liver

To determine whether Epo is a direct transcriptional target of hepatic RA signaling in vivo, we performed chromatin immunoprecipitation (ChIP) on E13.5 mouse liver samples. Previous studies have shown that Epo harbors a conserved DR2 RARE element in its 3’ enhancer that is required for RA-regulated transcription in transfected cell lines (Makita et al., 2005). Therefore, we carried out ChIP studies to ascertain whether RAR proteins are recruited to this RA response element in embryonic liver. ChIP results demonstrate that all three RA receptors (RARα, RARβ and RARγ) exhibit robust binding to the Epo RARE, whereas no association was observed in a region upstream of Epo and no signal was observed with IgG control (Fig. 5A,B). These findings provide strong evidence that Epo expression in embryonic liver is directly induced by RA signaling.
EPO signaling induces expression of Igf2 in mouse epicardial cells

Next, we determined whether secreted EPO acts in the epicardium to stimulate production of a downstream mitogen that could facilitate compact zone growth. To date, which mitogen(s) are produced by the epicardium to induce compact zone formation remains elusive. We have recently derived a mouse embryonic ventricular epicardial cell line called MEC1 and tested expression of various mitogens (P.L. and H.M.S., unpublished). We found that expression of Igf2 is upregulated in MEC1 cells upon EPO treatment. Our data shows that 10 ng/ml EPO in serum-free culture medium increased IGF2 mRNA levels by approximately 3.5-fold in MEC1 cells, whereas treatment of MEC1 cells with 1 µM RA did not increase IGF2 mRNA above control levels (Fig. 6A). We conclude from these findings that EPO, but not RA, can induce Igf2 in epicardial cells in vitro.

Loss of Raldh2 or Rxra function results in loss of Igf2 expression in the epicardium

We investigated whether Igf2 expression in epicardium is affected by loss of RA signaling in vivo. Heart sections from wild-type, rescued Raldh2−/− and Rxra−/− E12.5 embryos were examined by in situ hybridization to visualize Igf2 mRNA. We observed that E12.5 rescued Raldh2−/− mutants and that Rxra−/− mutants exhibited a loss of Igf2 mRNA in the epicardium (Fig. 6B). These findings demonstrate a dependency of epicardial Igf2 expression on RA signaling. However, RA does not act directly in the epicardium as our findings above indicate that Rxra−/− embryos retain epicardial RA signaling, and RA treatment of MEC1 epicardial cells does not induce Igf2. Together, these in vivo and in vitro data point to a possible RA-EPO-IGF2 signaling axis from liver to heart.

EPO treatment rescues epicardial Igf2 expression and cardiomyocyte proliferation

In order to establish the existence of an RA-EPO-IGF2 signaling axis, we analyzed EPO-treated heart organ cultures for epicardial Igf2 induction and ventricular cardiomyocyte proliferation. In order to determine whether EPO can stimulate Igf2 expression in embryonic epicardium, we cultured E11.5 wild-type and Raldh2−/− hearts with or without the addition of EPO to the culture medium. After 18 hours in culture, hearts were sectioned and analyzed for expression of Igf2 by in situ hybridization. Both control and EPO-
treated wild-type hearts exhibited \textit{Igf2} mRNA in the epicardium (Fig. 7A,B). Control \textit{Raldh2} \textsuperscript{−/−} hearts lacked \textit{Igf2} mRNA in the epicardium but EPO treatment of \textit{Raldh2} \textsuperscript{−/−} hearts was able to rescue the appearance of \textit{Igf2} mRNA in the epicardium (Fig. 7C,D). These findings provide further evidence that EPO can stimulate induction of epicardial \textit{Igf2}.

Next, we examined the proliferation rate of cardiomyocytes in E11.5 wild-type and \textit{Raldh2} \textsuperscript{−/−} heart organ cultures. The proliferation rate of ventricular cardiomyocytes in untreated \textit{Raldh2} \textsuperscript{−/−} mutant hearts was significantly lower than that observed in wild-type hearts, but we detected a significant increase in the proliferation rate of \textit{Raldh2} \textsuperscript{−/−} ventricular cardiomyocytes following EPO treatment (Fig. 8). The cardiomyocyte proliferation rates for wild-type hearts (EPO-treated and untreated) and EPO-treated \textit{Raldh2} \textsuperscript{−/−} hearts were not significantly different (Fig. 8). Taken together with the findings above, we conclude that EPO treatment can rescue the observed loss of \textit{Igf2} expression and reduced cardiomyocyte proliferation in RA-deficient hearts, further strengthening our proposed model of ventricular compact zone growth.

\section*{DISCUSSION}

\textbf{RA-EPO-IGF2 signaling axis from liver to heart is required for myocardial expansion}

The epicardium is thought to secrete one or more diffusible factors that stimulate proliferation of ventricular cardiomyocytes but the identity of the secreted factor(s) remains elusive and upstream regulators of epicardial mitogen production are unclear. The findings presented in this study suggest a novel mechanism for ventricular compact zone expansion through a RA-EPO-IGF2 signaling axis extending from liver to heart (Fig. 9). Thus, we suggest that RA signaling affects epicardial function in a tissue-nonautonomous fashion by inducing \textit{Epo} expression in hepatic tissues, leading to secretion of the glycoprotein hormone EPO and binding to the EPO receptor in the epicardium. EPO produced in the liver might preferentially reach the epicardium by diffusion from the nearby liver mesothelium through the pericardioperitoneal canals that persist until E13.5-E14.5 (Kaufman, 1992), or EPO could reach the heart by secretion into the bloodstream. We propose that EPO signaling in the epicardium then induces production of IGF2, which acts as a promoter of cardiomyocyte proliferation in the ventricular compact zone. This model is supported by genetic studies demonstrating ventricular myocardial thinning in mice carrying null mutations of \textit{Epo} or \textit{Epor} (Wu et al., 1999). In addition, we demonstrate that EPO treatment of \textit{Raldh2} \textsuperscript{−/−} hearts can rescue epicardial \textit{Igf2} expression and ventricular cardiomyocyte proliferation. Signaling between heart and liver has also been observed earlier in development in studies demonstrating that FGF signaling from the heart can induce endoderm to undergo liver formation (Jung et al., 1999).

\textbf{RA signaling in the epicardium is not required to stimulate myocardial expansion}

Previous studies suggested that an RA signaling event in the epicardium is necessary for ventricular myocyte proliferation (for a review, see Lavine and Ornitz, 2008). This mechanism was supported by two previous genetic experiments that resulted in ventricular myocardial thinning, one employing a dominant-negative RAR\textit{α} construct expressed in the epicardium under the control of the human keratin-18 promoter (Chen et al., 2002), and another using \textit{Gata5-Cre} for conditional deletion of \textit{Rxra} in the epicardium (Merki et al., 2005). These mouse models used promoter elements driving \textit{Cre} expression in the epicardium but not other cardiac tissues, however, both promoters are also expressed in other septum transversum mesenchyme (STM) derivatives including the mesothelium around the liver and the adjacent liver tissue potentially derived from ingestion of the mesothelium (Thorey et al., 1993; Merki et al., 2005). Therefore, both the dominant-negative RAR\textit{α} and \textit{Gata5-Cre:Rxra} \textsuperscript{−/−} conditional mutant could have acted in STM-derived liver progenitors to reduce hepatic \textit{Epo} expression; here, we demonstrate that the latter genetic model does exhibit a loss of hepatic \textit{Epo} expression.

As \textit{Rxra} \textsuperscript{−/−} hearts exhibit myocardial compact zone thinning but maintain epicardial RA signaling (potentially through a redundant function of RXR\textit{β} (Wendling et al., 1999)), the studies reported here suggest that RA synthesis detected in the epicardium does not function to stimulate compact zone expansion. This conclusion is further strengthened by data demonstrating that epicardial RA activity initiates marginally at E11.5 and robustly only at E12.5 after compact zone expansion (which begins at E10.5) is well underway. By contrast, \textit{Raldh2} expression and RA activity are detected by E10.5 in the liver mesothelium (Wang et al., 2006; Ijpenberg et al., 2007), which our findings suggest is the RA target tissue required for myocardial compact zone expansion. A recent study suggested that differentiation of cardiac progenitors contributing to compact zone growth is regulated by epicardial RA (Lin et al., 2010) but our studies suggest that this is due to RA signaling outside the heart as we demonstrate normal epicardial RA signaling in \textit{Rxra} \textsuperscript{−/−} hearts. Although we demonstrate that epicardial RA signaling is unnecessary for compact zone growth, epicardial RA might function in coronary vessel development as recently suggested (Azambuja et al., 2010; Lin et al., 2010), or in a regenerative response to heart injury as suggested by studies in zebrafish (Lepilina et al., 2006). However, as the epicardium and liver mesothelium are both derived from the STM, which expresses
Raldh2, one might speculate that expression of Raldh2 and synthesis of RA in the epicardium could be an unnecessary by-product of their common lineage. Although we show that Raldh2 expression in liver STM derivatives performs a necessary function, expression of Raldh2 in epicardial STM derivatives might have no significant function in mouse, and could exist as a vestigial evolutionary remnant.

Septum transversum derived progenitor cells play important roles during organogenesis

Recent findings have made it increasingly clear that STM-derived progenitor cells are required for maturation and growth of both heart and liver. Independent studies have emphasized parallel developmental mechanisms between these two organs and have specifically focused on the STM-derived pluripotent progenitors. The liver bud, which develops after cardiogenic mesoderm formation, is required for proepicardial organ induction in naïve chicken mesoderm (Ishii et al., 2007). Mesenchymal cells originating in the STM are able to differentiate into hepatic stellate cells and sinusoidal endothelial cells that migrate into the liver, providing vasculature and mitogens for liver expansion (Asahina et al., 2009). Also, RA synthesis controlled by Raldh2 downstream of Wt1 is required for the expansion of these hepatic stellate cell progenitors (Lijnenberg et al., 2007). Mesenchymal cells originating in the STM are able to differentiate into hepatic stellate cells and sinusoidal endothelial cells that migrate into the liver, providing vasculature and mitogens for liver expansion (Asahina et al., 2009). Also, RA synthesis controlled by Raldh2 downstream of Wt1 is required for the expansion of these hepatic stellate cell progenitors (Lijnenberg et al., 2007), which are known to express Epo (Maxwell et al., 1994). Furthermore, RA generated by Raldh2 is necessary for remodeling of subcoelomic mesenchyme during formation of the cardiac sinus horns (Norden et al., 2010), thus demonstrating that RA signaling in STM derivatives is required for organogenesis. Liver hypoplasia observed in rescued Raldh2–/– embryos (Wang et al., 2006) might therefore be the result of disrupted STM-derived cell differentiation and expansion. During ventricular maturation, the STM-derived epicardium facilitates an analogous process. The epicardium provides essential mitogens for compact zone proliferation and epicardial-derived cells differentiate into smooth muscle cells and cardiac fibroblasts, indispensable cell lineages for cardiac architecture and coronary vessel formation (Lie-Venema et al., 2007). However, our findings suggest that RA signaling in STM cells contributing to the epicardium is dispensable for compact zone formation.

Hepatic RA signaling acts through EPO to stimulate epicardial IGF2 expression

Our studies provide evidence for an RA-EPO signaling pathway from liver to heart that stimulates expansion of the ventricular compact zone. We demonstrate that liver expression of Epo requires not only Rxra but also RA synthesis controlled by Raldh2 in liver mesothelium. EPO signaling in the epicardium has been shown to stimulate myocardial expansion (Wu et al., 1999; Stuckmann et al., 2003), but target genes for EPO signaling in the epicardium have not been described prior to this study. Here, we show that treatment of MEC1 cells with EPO (but not RA) induces Igf2 expression. Also, loss of Raldh2 or Rxra function in vivo results in loss of hepatic Epo expression and epicardial Igf2 expression. Furthermore, EPO treatment of RA-deficient hearts rescues both epicardial Igf2 expression and ventricular cardiomyocyte proliferation. Together, these findings provide evidence that hepatic RA signaling induces Epo, which results in...

Fig. 8 Cardiomyocyte proliferation in heart organ culture is rescued by EPO treatment. Hearts dissected from E11.5 wild-type (WT) or Raldh2–/– mutant mice were cultured for 18 hours in the absence of EPO (control) or with EPO (+EPO), then examined immunohistochemically for cardiomyocytes (MF20; red), dividing cells (Ki67; green), and nuclei (DAPI; blue). Control or EPO-treated wild-type hearts exhibited significantly more proliferating cardiomyocytes (MF20+, Ki67+) compared with control Raldh2–/– hearts, but EPO treatment of Raldh2–/– hearts restored the cardiomyocyte proliferation rate to wild-type levels (n=2 for each genotype). Data are mean ± s.d.

Fig. 9. RA-EPO-IGF2 signaling axis from liver to heart. We propose a model for control of myocardial compact zone formation that involves a sequence of three signaling pathways extending from liver to heart: (1) RA signaling generated by hepatic RALDH2 and RXRα induces hepatic Epo; (2) EPO secreted by the liver results in epicardial EP signaling needed to induce Igf2; (3) Igf2 secreted by the epicardium results in myocardial IGF2 signaling needed to stimulate ventricular myocardial growth. INSr/IGF1r represents the receptors for IGF2.
epicardial EPO signaling that induces the Igf2 needed for ventricular compact zone growth. Our conclusion is supported by studies demonstrating that loss of IGFR2, a receptor that negatively regulates IGF2 signaling, leads to cardiac hypertrophy characterized by a 3-fold larger heart with a markedly increased compact zone myocardium (Lau et al., 1994). Lastly, cardiomyocytes derived from human embryonic stem cells require IGF signals for proliferation (McDevitt et al., 2005). Taken together with our findings, we suggest that IGF2 functions as an important epicardial-derived mitogen needed for cardiomyocyte expansion downstream of EPO and RA signaling.

It is intriguing to speculate about the evolutionary implications of our model of myocardial growth. Cross-talk between the developing heart and liver at mid-gestational stages appears to satisfy the growing need of the embryo for sufficient oxygen and nutritional supply carried by the bloodstream. Embryonic hematopoiesis begins shifting from the yolk sac to the liver when ventricular compact zone expansion begins. Therefore, RA-EPO-IGF2 signaling provides a mechanism to coordinate embryonic liver hematopoiesis with cardiac growth, a prerequisite for embryonic survival. Moreover, coelomic mesothelial cells originating in the lateral plate mesoderm and giving rise to the STEM and other types of mesenchyme, contribute cells and signaling cues not only to hepatic and cardiac tissues but also to the lung and gut (Wilm et al., 2005; Que et al., 2008). A broader understanding of signals governing coelomic organ development and multipotent precursor contributions will further deepen our insight into mechanisms vital for normal embryonic growth and could open avenues for new strategies to counteract congenital birth defects.

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Supplementary material

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References


