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Cholesterol Metabolism: the Main Pathway Acting Downstream of Cytochrome P450 Oxidoreductase in Skeletal Development of the Limb\textsuperscript{7,\dagger}

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Cytochrome P450 oxidoreductase (POR) is the obligate electron donor for all microsomal cytochrome P450 enzymes, which catalyze the metabolism of a wide spectrum of xenobiotic and endobiotic compounds. Point mutations in POR have been found recently in patients with Antley-Bixler-like syndrome, which includes limb skeletal defects. In order to study P450 function during limb and skeletal development, we deleted POR specifically in mouse limb bud mesenchyme. Forelimbs and hind limbs in conditional knockout (CKO) mice were short with thin skeletal elements and fused joints. POR deletion occurred earlier in forelimbs than in hind limbs, leading additionally to soft tissue syndactyly and loss of wrist elements and phalanges due to changes in growth, cell death, and skeletal segmentation. Transcriptional analysis of E12.5 mouse forelimb buds demonstrated the expression of P450s involved in retinoic acid, cholesterol, and arachidonic acid metabolism. Biochemical analysis of CKO limbs confirmed retinoic acid excess. In CKO limbs, expression of genes throughout the whole cholesterol biosynthetic pathway was upregulated, and cholesterol deficiency can explain most aspects of the phenotype. Thus, cellular POR-dependent cholesterol synthesis is essential during limb and skeletal development. Modulation of P450 activity could contribute to susceptibility of the embryo and developing organs to teratogenesis.

The P450 system is best characterized for its role in the metabolism and detoxification of environmental chemicals in adult liver (57). However, some subfamilies of P450 enzymes also have a pivotal role in metabolizing endogenous compounds such as hormones and fatty acids (4, 63). Cytochrome P450 oxidoreductase (POR) is the obligate electron donor for all microsomal cytochrome P450 enzymes (Cyps) and, in the absence of POR, these enzymes are catalytically inactive (3). There are more than 100 P450 enzymes in mice and over 50 in humans, and the particular profiles of P450s, many of which are polymorphic, determine an individual’s response to drugs (58, 59). Surprisingly, however, rather little is known about the function of these enzymes in embryonic development, although the recent discovery of point mutations in POR in patients with Antley-Bixler-like syndrome is direct evidence of their importance during human development (27, 29).

Several studies have shown that POR and genes encoding P450 enzymes are expressed in mouse embryos. POR expression has been detected from preimplantation stages onward (81), while the most comprehensive studies of expression of cytochrome P450s have revealed that genes encoding several of these enzymes are temporally regulated over four stages of development (13, 14); temporal regulation has also been shown for Cyp1A1 in more detail (7). These P450 studies, however, were based on reverse transcription-PCR and did not give any information about tissue localization.

Deletion of individual P450 genes in mice has uncovered some essential developmental roles. Members of the Cyp26 subfamily of P450s are involved in degrading retinoic acid, an important signal in the development of many parts of the embryo. Retinoic acid concentration in embryos is regulated via a feedback mechanism (19, 66), with production and degradation of retinoic acid taking place in complementary domains (83). Deletion of Cyp26 genes leads to increased levels of retinoic acid and developmental defects (70, 96). In addition, cholesterol, synthesized by Cyp51 and metabolized by other Cyp family members to produce steroid hormones and vitamin D (56, 65), is known to be essential for normal development (69).

Another approach that has been taken to understand the essential role of the P450 system in embryonic development has been the deletion of POR and, as a consequence, the removal of all microsomal P450 function. This approach avoids problems with multiplicity and functional redundancy of Cyp enzymes. POR deletion in mice leads to elevated retinoic acid levels and embryonic lethality prior to organogenesis and limb
initiation, implicating retinoic acid metabolism as the major P450 pathway downstream of POR function in the early embryo. When retinoic acid levels were reduced either by feeding POR-deficient mice with a retinoid-deficient diet (64) or, genetically, by crossing them with mice haploinsufficient for the retinoic acid-generating enzyme Raldh2 (67), embryonic development improved, some POR<sup>lox/lox</sup>; Raldh2<sup>lox/lox</sup> embryos surviving until embryonic day 13.5 (E13.5). Knockout of the membrane-binding domain of POR (75) also resulted in longer survival.

We have focused here on the P450 system in limb development. The limb is one of the best-studied organ systems in vertebrate embryos and a well-known target for teratogens. POR has been reported to be expressed in E12.5 mouse limb mesenchyme and later, at E13.5, at high levels in joint-forming regions and perichondrium (43). Limb buds in POR<sup>lox/lox</sup>; Raldh2<sup>lox/lox</sup> embryos surviving until E13.5 had anteroposterior patterning defects (68), and limb buds in embryos in which the membrane domain of POR was knocked out were described as abnormal (75). Furthermore, some patients with POR mutations have defects in the limb skeleton (29). We generated a conditional knockout mouse line by crossing Prx1-Cre mice (51) to mice in which both alleles of POR are flanked by loxP sites (36). The Prx1-Cre mouse line has been widely used to knock out genes specifically in limb bud mesenchyme, which gives rise to the skeleton and other connective tissues (1, 15, 49, 84). Gene knockout has been reported to occur at E9.5 in forelimb buds but slightly later in hind limb buds (51). This conditional approach creates a peripheral dysfunction, thus avoiding the embryonic lethality of a systemic POR knockout.

We found that POR deletion in mouse limb buds leads to defects in both patterning and skeletogenesis. Microarray analysis suggested the involvement of P450 pathways participating in retinoic acid, cholesterol, and arachidonic acid metabolism. All trans-retinoic acid was elevated, while cholesterol was re-supplied in retinoic acid, cholesterol, and arachidonic acid metabolism. All trans-retinoic acid was elevated, while cholesterol was re-supplied.

**Western blotting, immunohistochemistry, and skeletal staining.** POR detection in whole-limb protein extracts was carried out with a polyclonal antibody raised to human POR (35). For anti-pH3 staining, sections were blocked with 10% fetal calf serum–1% bovine serum albumin in phosphate-buffered saline, incubated with primary antibody (1:100; Upstate, New York, NY) and detected with anti-rabbit-Alexa 488 (1:200; Molecular Probes, The Netherlands). Fluorescence was taken and the images were laser-scanned before data acquisition. Four acquisition sequences were collected and averaged to improve the signal-to-noise ratio and reduce artifacts. The acquisition parameters were as follows: pixel size, 256 by 256; field of view, 30.0 by 30.0 by 30.0 mm; and voxel dimensions, 120 by 120 by 120 μm. Imaging was performed with Openlab 4.1 and Adobe Photoshop CS2. Anterior of the limb bud is up and posterior is down in all images. Samples for histology were fixed in 4% paraformaldehyde for several days and processed according to standard staining protocols. Alcian Blue and Alizarin Red staining for cartilage and bone, respectively, was carried out as published previously (54), and limbs were measured under a binocular microscope with a vernier caliper.

**TUNEL stain and in situ hybridization.** TUNEL (terminal deoxynucleotidyl transferase-mediated dUTP-biotin nick end labeling) staining was performed according to the manufacturer’s instructions on 14-μm frozen sections (in situ cell death detection kit fluorochrome, Roche, Germany).

Whole-mount in situ hybridizations were carried out as described previously (67). Riboprobes were either cloned or kindly provided by Se-Jin Lee (CDS5), Robert Hill (Mdx2), Klaus van de Mark (Col2A and Col10), Michael Wegner (Ihh and Sox9), Tomoko Iwata (Patched1), Andrea Voortkamp (Gli1), Bridg Hogan (FoxC1), Pascal Dallol (Raldh2), and Denis Duboule (HoxD probes). Images were taken and processed as described above. In situ hybridizations were carried out on three independent samples with little variability in the results, unless stated otherwise.

Whole-mount limb buds of Cyp26B1 and Raldh2 in situ hybridization experiments were processed and scanned by using optical projection tomography (74). 3D reconstruction of data was performed using AMIRA software.

**Retinoid and sterol quantification.** After genotyping, forelimb and hind limb buds of four E12.5 embryos were pooled separately to give single samples for forelimb buds and hind limbs, respectively. Poolems were made from both normal and CKO embryos. Pooled limb buds (three pools) were homogenized in ice-cold phosphate-buffered saline with a motorized homogenizer (Pro Scientific, Inc., Oxford, CT), and retinoids were extracted with ice-cold 2-propanol containing 13C-labeled all-trans retinoic acid (atRA) as an internal standard. An aliquot was injected into a 4000 Q TRAP LC-MS/MS instrument with APCI ionization (Applied Biosystems, California). The liquid chromatography-mass spectrometry conditions were as described previously (33), except that the separating column was an ABZ Plus (75 by 3 mm [inner diameter], 3-μm particles; Supelco, Pennsylvania). The entire procedure was performed under red light.

For sterol quantifications, left and right limb buds of E13.5 genotyped embryos were pooled to give single samples for forelimbs and hind limbs, respectively.
Abbreviations: A, autopod; Fe, femur; Fi, fibula; Hu, humerus; Ra, radius; S, stylopod; Ti, tibia; Ul, ulna; Z, zeugopod.

Processes on humerus and femur (arrows) are missing or reduced. CKO forepaws show characteristic splaying of digits 3 and 4 (arrowhead). Two carpal bones (compare insets), no secondary ossification centers (open arrowhead), and a reduced number of phalanges in digits 1, 2, and 5.

Microarray analysis. Total RNA was extracted with TRIZol (Life Technologies, United Kingdom) according to the manufacturer’s guidelines, except for the addition of 1 μl of linear acrylamide (Ambion, Inc., Texas) at precipitation, from pooled, genotyped E12.5 forelimb buds (four limb buds per pool). Five pools of control and five pools of CKO forelimb total RNA were prepared. Microarray analysis was carried out using standard protocols on Genechip Mouse 430 2.0 arrays (Affymetrix, United Kingdom). Amplified RNA was prepared from 5 μg of total RNA by using a GeneChip 3’ expression one cycle target labeling kit (Affymetrix) according to the manufacturer’s recommendations. After overnight hybridization, arrays were processed using the Affymetrix fluidsation station. Obtained images were processed with GCOS software, and the resulting CEL files were analyzed. Normalization of experimental data was done with Expression Console software (Affymetrix) using the PILEK algorithm.

Statistical analysis was carried out using the LIMMA (36) module in Bioconductor software (31). Differences between CKO and the control condition were examined by a modified t test, where the LIMMA eBayes correction was used to produce a moderated T-statistic, thereby shrinking estimated sample variances toward a pooled estimate, resulting in far more stable inference. The top 50 transcripts with the lowest false discovery rate were annotated using NetAffx website (http://www.affymetrix.com/analysis/index.affx) and subjected to pathway analysis with GenMAPP software (18). The complete data set is available at http://www.ebi.ac.uk/arrayexpress (E_TABM_367).

RESULTS

Conditional deletion of POR leads to limb malformations. In order to investigate POR function specifically in the developing limb bud and skeleton, we generated a conditional knock-out mouse line, Prx1-Cre; PORlox/lox (CKO), by crossing Prx1-Cre mice (51) to mice with both alleles of POR flanked by loxP sites (36). We monitored POR knockout at both transcript and protein level in limb buds of Prx1-Cre; PORlox/lox embryos (Fig. 1). POR transcripts were absent and POR protein was moderately reduced at E10.5 and undetectable at E11.5 in forelimb buds (compare Fig. 1C to A; Fig. 1I), whereas, in hind limb buds, POR transcripts and protein were present at E10.5, and the protein was still faintly detectable at E11.5 (compare Fig. 1H to F; Fig. 1I).

The conditional deletion of POR during limb bud development resulted in limb malformations. In 7 day Prx1-Cre; PORlox/lox mice, the limbs were clearly abnormal (Fig. 2A), with forelimbs being much shorter and more malformed than hind limbs (57% of the length of control forelimbs and 79% of...
control hind limbs, respectively). This difference in severity of the defects is consistent with the difference in developmental timing of knockout with POR being deleted at an earlier stage in the forelimb compared to the hind limb. More detailed external examination of the forelimbs also revealed that the digits appeared stunted and fused except for a pronounced interdigital space between digits 3 and 4 (Fig. 2A, compare insets).

Skeletal preparations of the limbs of 7 day Prx1-Cre; PORlox/lox mice showed that all bones were short and misshapen in both forelimbs and hind limbs with forelimb elements again more affected than those in hind limbs (Fig. 2B; see Table S1 in the supplemental material for measurements of the lengths of individual bones in forelimbs and hind limbs and details of skeletal phenotype analysis). Long bones in the stylopod (upper part of the limb, i.e., humerus in forelimb and femur in hind limb; Fig. 2B) and zeugopod (middle part of the limb, i.e., radius and ulna in the forelimb and tibia and fibula in the hind limb, Z in Fig. 2B) were thinner. Processes on humerus and femur were reduced or absent (Fig. 2B), no secondary ossification centers were seen (Fig. 2B) and in the hind limbs, the fibula was very bent and tibia and fibula were not fused (Fig. 2B). In addition, joints, especially at the knee and elbow, were malformed and swollen and, in about half of the CKO forepaws, fusion of digits and joints was noted (see Table S1 in the supplemental material). No skeletal patterning defects were seen in CKO hind limbs, but in CKO forelimbs digits 1, 2, and 5 lacked one phalange each (Fig. 2B), and six out of eight carpal bones were absent, leaving most likely hamate and central carpal bones (Fig. 2B, compare insets). The characteristic splaying of digits 3 and 4 in the forelimb was also clear in the skeletal preparations (Fig. 2B).

Postnatal consequences of functionally inactivating POR in the limbs were monitored over 2 months. The growth of both forelimbs and hind limbs was impaired with the forelimb continuing to be more affected (see Table 1 in the supplemental material). Comparison of the mineralized tissue of CKO forelimbs and hind limbs was impaired with the forelimb compared to the hind limb. More detailed examination of the forelimbs also revealed that the digits appeared stunted and fused except for a pronounced interdigital space between digits 3 and 4 (Fig. 2A, compare insets).

FIG. 2. Embryonic development of forelimb and skeleton in conditional POR knockout mice. In order to identify critical events leading to changes in Prx1-Cre; PORlox/lox mice, we followed forelimb development during embryogenesis because POR is deleted earlier in forelimbs than in hind limbs (Fig. 1), and this leads to more marked skeletal defects and also to patterning defects (Fig. 2B). At E10.5 and E11.5, stages at which POR protein was markedly reduced or no longer detectable, respectively (Fig. 1I), no change in the size and shape of forelimb buds was observed (compare Fig. 1A to C and Fig. 1E to G). External inspection of E12.5 forelimb buds (Fig. 4A and B) also did not reveal major differences between control and Prx1-Cre; PORlox/lox embryos, although CKO paws were slightly stunted (Fig. 4B). Chondrogenic condensations were similar in both genotypes (data not shown). In contrast, at E13.5, exter-
nal changes were immediately obvious in CKO forelimbs (Fig. 4C and D), and these were accentuated at E14.5 (Fig. 4E and F) and E17.5 (Fig. 4G and H). The outgrowth of digits in E14.5 Prx1-Cre; PORlox/lox limbs was reduced, as were indentations between digits 1, 2, and 3 and between digits 4 and 5, leading to soft tissue webbing especially involving digits 1, 2, and 3 (Fig. 4E and F). The indentation between digits 3 and 4, however, still developed so that these digits splayed apart. Alcian Blue staining at E14.5 also indicated delayed development of interphalangeal joints compared to control limbs (compare Fig. 4E and F, insets). In E17.5 CKO limbs, only digits 3 and 4 were clearly separated (Fig. 4H, arrowhead), and digits 1 to 3 appeared fused (Fig. 4H) due to soft tissue webbing (compare to Fig. 4G).

Skeletal preparations of E17.5 forelimbs not only showed the characteristic splaying of digits 3 and 4 in the CKO but also that stylo- and zeugopod were reduced in length and the humeral process was absent (Fig. 4I and J), while in the paw, only two carpal bones were present (Fig. 4J, inset, arrow, compare to 4I, inset), and the phalanges of digits 1, 2, and 5 were not fully segmented (Fig. 4J [compare to 4I]). Other postnatally obvious aspects of the phenotype had not yet appeared, in particular thinning of the long bones and swollen joints.

Soft tissue webbing in CKO forelimbs suggested impairment of interdigital cell death. In situ hybridizations on E12.5 limb buds for Msx2 (71), a gene encoding a homeobox transcription factor associated with interdigital preapoptotic cells, showed that Msx2 expression was markedly reduced in all interdigital spaces in CKO forelimbs except between digits 3 and 4 (compare Fig. 5A and B). TUNEL assays performed on sections of E13.5 limb buds confirmed reduced interdigital cell death between anterior digits although apoptosis appeared increased subapically (Fig. 5C and D). A decrease in apoptosis in CKO forelimb buds did not seem consistent with smaller paws, but overall proliferation was also reduced, as shown by immunostaining against phosphorylated histone H3 (compare Fig. 5E and F).

Another feature of Prx1-Cre; PORlox/lox forelimbs was failure to complete digit segmentation, leading to loss of a phalanx in digits 1, 2, and 5. In order to investigate phalanx segmentation, the expression of GDF5, a gene encoding a transforming growth factor specifically expressed in joint-forming regions of developing limb buds (79, 80), was examined. No difference was detected at E12.5 between normal and CKO forelimb buds (Fig. 5G and H). At E13.5, the time at which it has been reported that POR is expressed at high levels in joint-forming regions (43), GDF5 expression in CKO forelimbs was comparable to controls in digits 3 and 4 even though these were clearly reduced in length but compressed to one domain at both edges of the handplate (Fig. 5I and J). At E14.5, the handplate of Prx1-Cre; PORlox/lox limb buds appeared even more stunted and GDF5 expression was generally increased even in interdigital regions, making it difficult to define the presumptive joints (Fig. 5K and L).

The patterning defect of missing wrist elements and phalanges prompted an investigation of expression of HoxD11-HoxD13 genes known to be involved in development of skeletal elements in the distal limb (98, 99). No changes could be detected at either E12.5 or even at E13.5 when CKO forelimb buds were clearly misshapen (data not shown). Because patterning of the anterior and posterior autopods was most affected, Tbx3, normally expressed in anterior and posterior stripes in developing limb buds and implicated in digit speci-
fication (82, 86), was investigated, but again no difference in gene expression was seen in the CKO (data not shown).

Chondrogenesis of forelimb skeleton in Prx1-Cre; PORlox/lox mice. In order to investigate skeletal development in CKO forelimbs in more detail, we assessed expression of Sox9 (Sry-related HMG box 9), a gene encoding a transcription factor required for mesenchymal condensation and chondrogenesis (1, 93). Sox9 expression at E12.5 was very similar in forelimbs of both, control and CKO embryos consistent with Alcian Blue staining at this stage (data not shown) but by E13.5, Sox9 expression appeared broader in digits of CKO forelimbs with less sharp boundaries and less definition around joint forming regions (compare Fig. 6A and B). Branching of digit 2 primordium was observed in one of three cases (Fig. 6B).

To study specific chondrogenic differentiation states, we examined the expression of Collagen 2A (Col2A), a transcriptional target of Sox9 in proliferating chondrocytes (60), and Indian hedgehog (Ihh) and Collagen 10 (Col10), expressed in prehypertrophic and hypertrophic chondrocytes, respectively (22, 87). Col2A was expressed throughout all digit primordia similar to Sox9 at both E12.5 (not shown) and E13.5 (compare Fig. 6A and B with Fig. 6C and D) with broader, less-well-defined expression in CKO forelimbs; in one of three cases digit 2 primordium was observed in one of three cases (Fig. 6B).

To identify gene expression changes in Prx1-Cre; PORlox/lox forelimb buds, a statistical analysis of all differentially expressed genes was performed. Surprisingly, expression of only 0.1% of genes represented on the array was found to be significantly changed with a low false discovery rate (Fig. 7B). These top 50 probe sets represent 39 different genes. As expected, Msx2 was among downregulated transcripts (Fig. 7B differed from embryo to embryo, e.g., more fan-shaped in one and more rod-shaped and shorter in another.

Microarray analysis. In order to gain insights into how the phenotype described above is related to function of POR and P450 enzymes during mouse limb development, we performed whole-genome expression analysis and evaluated the results of an average of five arrays per genotype. Transcriptional changes were investigated at E12.5, the time before marked morphological differences were obvious but at which there were already clear alterations in Msx2 expression.

A total of 60 mouse P450 genes have annotated probe sets on the 3'-expression array, and 14 out of these were found to be expressed in E12.5 forelimb buds (Fig. 7A; according to present calls in all five control arrays). For two, Cyp2d22 and Cyp20a1, enzymatic substrates of their proteins are not yet known. The gene encoding the retinoic acid metabolizing enzyme, Cyp26a1, was expressed (Fig. 7A, green). Another member of this subfamily, Cyp26b1, was not represented on the array but is known to be expressed in limb buds at this stage (39, 70, 96). All other P450s present were involved in either arachidonic acid (Fig. 7A, black) or cholesterol (Fig. 7A, red) metabolism.

To study skeletal development in CKO forelimbs in more detail, we assessed expression of Sox9 (Sry-related HMG box 9), a gene encoding a transcription factor required for mesenchymal condensation and chondrogenesis (1, 93). Sox9 expression at E12.5 was very similar in forelimbs of both, control and CKO embryos consistent with Alcian Blue staining at this stage (data not shown) but by E13.5, Sox9 expression appeared broader in digits of CKO forelimbs with less sharp boundaries and less definition around joint forming regions (compare Fig. 6A and B). Branching of digit 2 primordium was observed in one of three cases (Fig. 6B).

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The shapes and sizes—but not the locations—of both control embryos.

expression domains were variable. No variation was observed for con-

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enzymes and sterol-sensing or transport proteins and the P450
zymes involved in cholesterol metabolism, Cyp26b1 and Raldh2, in CKO limb buds at E11.5 and E12.5 using whole-mount in situ hybridization. Cyp26b1 was chosen rather than Cyp26a1 because both genes show essentially the same regulation (66), but Cyp26b1 is better characterized in limb development (96), and we have previously shown an upregulation of Cyp26a1 in POR-deficient limb buds (67). Only minor differences were detectable at E11.5 between control and Prx1-Cre; PORlox/lox forelimb buds for Cyp26b1 (Fig. 8A and C), whereas Raldh2 already appeared to be downregulated in CKO forelimbs (compare Fig. 8E and G). At E12.5, expression patterns for both genes agreed with the microarray results with Cyp26b1 ectopically expressed in forelimbs (Fig. 8I and K), whereas Raldh2 expression domains were smaller (Fig. 8M and O). There were no obvious differences in expression of either gene in hind limb buds at E11.5 or E12.5 (Fig. 8B, D, F, H, J, L, N, and P). A three-dimensional reconstruction of whole-mount in situ hybridization specimens at E12.5 (Fig. 8Q to T) showed that interdigital mesenchyme between forelimb digits 3 and 4 was the only domain with nonoverlapping expression Cyp26b1 and Raldh2. It was development of this interdigital space that led to the characteristic spaying of digits 3 and 4 in CKO forelimbs (see for example, Fig. 2A and Fig. 4F and H).

Direct retinoid measurements in E12.5 limb buds showed elevated atRA in CKO forelimb buds, while the levels of atRA were similar in forelimb buds of control embryos and both CKO and control hind limb buds (Fig. 8U). The elevation of atRA resulted in around a 50% increase in the ratio of atRA to retinol in CKO forelimbs compared to control forelimbs in which the ratio was similar to that in both CKO and control hind limbs. From these results, we conclude that POR inactivation led to reduced retinoic acid degradation, resulting in accumulation of retinoic acid throughout E12.5 forelimb buds, except probably in the interdigital space between digits 3 and 4.

POR deletion leads to impaired cholesterol metabolism. The microarray results showed that genes encoding P450 enzymes involved in cholesterol metabolism, in particular Cyp51, are expressed in the handplate of E12.5 mouse forelimbs (Fig. 7A) and, since these require POR function for their activity, cholesterol homeostasis is predicted to be affected in CKO limb buds. It has been previously shown that reduced cholesterol leads to transcriptional upregulation of enzymes in the pathway (23). Strikingly, our microarray data showed that enzymes of almost the whole pathway, from acetyl coenzyme A all of the way down to cholesterol, were transcriptionally upregulated in CKO forelimbs (Fig. 7C and 9A, red), together

and C, blue; see also Fig. 5B), while another transcription factor, FoxC1, was upregulated (Fig. 7B and C, blue). Subsequent in situ hybridizations for FoxC1 (46) showed that this gene is expressed around forming digits at E12.5, and expression is elevated in CKO limb buds, in particular in the presumptive wrist region (Fig. 7D). The largest number of differentially expressed transcripts by far (23), however, was associated with cellular cholesterol homeostasis (Fig. 7B, red) and included transcripts encoding cholesterol synthesizing enzymes and sterol-sensing or transport proteins and the P450 enzyme, Cyp51 (see also Table S2 in the supplemental material). The gene encoding the retinoic acid metabolizing P450 Cyp26a1 was also on the list, together with the gene encoding the retinoic acid-synthesizing enzyme Raldh2 and transcription of these genes were up- and downregulated, respectively (Fig. 7B and C, green). The 12 remaining genes identified were either uncharacterized transcripts or unrelated to those described above.

Deletion of POR leads to excess retinoic acid. In the absence of POR, Cyp26 enzymes should be inactive, resulting in increased retinoic acid levels in CKO forelimb buds. It has previously been shown that genes encoding both retinoid-generating and retinoid-degrading enzymes are transcriptionally regulated by retinoic acid to maintain homeostasis (19, 66). The changes in transcript levels of retinoic acid metabolizing enzymes revealed by the microarray (Fig. 7B and C) therefore suggested the elevation of retinoic acid.

We confirmed changes in expression of genes involved in retinoic acid metabolism, Cyp26b1 and Raldh2, in CKO limb buds at E11.5 and E12.5 using whole-mount in situ hybridization. Cyp26b1 was chosen rather than Cyp26a1 because both genes show essentially the same regulation (66), but Cyp26b1 is better characterized in limb development (96), and we have previously shown an upregulation of Cyp26a1 in POR-deficient limb buds (67). Only minor differences were detectable at E11.5 between control and Prx1-Cre; PORlox/lox forelimb buds for Cyp26b1 (Fig. 8A and C), whereas Raldh2 already appeared to be downregulated in CKO forelimbs (compare Fig. 8E and G). At E12.5, expression patterns for both genes agreed with the microarray results with Cyp26b1 ectopically expressed in forelimbs (Fig. 8I and K), whereas Raldh2 expression domains were smaller (Fig. 8M and O). There were no obvious differences in expression of either gene in hind limb buds at E11.5 or E12.5 (Fig. 8B, D, F, H, J, L, N, and P). A three-dimensional reconstruction of whole-mount in situ hybridization specimens at E12.5 (Fig. 8Q to T) showed that interdigital mesenchyme between forelimb digits 3 and 4 was the only domain with nonoverlapping expression Cyp26b1 and Raldh2. It was development of this interdigital space that led to the characteristic spaying of digits 3 and 4 in CKO forelimbs (see for example, Fig. 2A and Fig. 4F and H).

Direct retinoid measurements in E12.5 limb buds showed elevated atRA in CKO forelimb buds, while the levels of atRA were similar in forelimb buds of control embryos and both CKO and control hind limb buds (Fig. 8U). The elevation of atRA resulted in around a 50% increase in the ratio of atRA to retinol in CKO forelimbs compared to control forelimbs in which the ratio was similar to that in both CKO and control hind limbs. From these results, we conclude that POR inactivation led to reduced retinoic acid degradation, resulting in accumulation of retinoic acid throughout E12.5 forelimb buds, except probably in the interdigital space between digits 3 and 4.

POR deletion leads to impaired cholesterol metabolism. The microarray results showed that genes encoding P450 enzymes involved in cholesterol metabolism, in particular Cyp51, are expressed in the handplate of E12.5 mouse forelimbs (Fig. 7A) and, since these require POR function for their activity, cholesterol homeostasis is predicted to be affected in CKO limb buds. It has been previously shown that reduced cholesterol leads to transcriptional upregulation of enzymes in the pathway (23). Strikingly, our microarray data showed that enzymes of almost the whole pathway, from acetyl coenzyme A all of the way down to cholesterol, were transcriptionally upregulated in CKO forelimbs (Fig. 7C and 9A, red), together
with the low-density lipoprotein receptor 1 (LDLR1) responsible for cholesterol uptake (6), \textit{Stard4}, the protein participating in intracellular cholesterol transport, the sterol-sensing protein Insig1, and the sterol regulatory element binding factor 2 (SREBP2), while the gene encoding ATP-binding cassette A1 (ABCA1) involved in lipid efflux from cells (72) was downregulated (Fig. 9B; see Table S2 in the supplemental material). Furthermore, direct measurements of sterols made in E13.5 control and CKO limbs (Fig. 9C) showed that the amount of cholesterol per CKO limb bud was reduced compared to con-

FIG. 7. Microarray analysis of E12.5 forelimb buds. (A) Transcripts of P450 enzymes in control embryos. The table shows all annotated Cyps with present calls (detection call above background) in all five arrays, together with the substrate specificities (according to the KEGG database). (B) Differentially expressed genes. All statistically significant probe sets with low false discovery rates represent 39 differentially expressed genes (0.1% of all genes on array). Genes involved in cholesterol homeostasis (red), retinoic acid-metabolizing enzymes (green), transcription factors (blue), and unknown transcripts or genes of unclassified function (yellow). The largest group (22) of upregulated genes in CKO samples is involved in cholesterol biosynthesis. (C) Changes of each differentially expressed gene, given next to each bar. Color coding as in panel B. Upregulation of cholesterol biosynthesis pathway indicates cholesterol deficiency through metabolic feedback. (D) In situ hybridization for \textit{FoxC1}. The expression pattern confirms microarray results.
control limb buds. Levels were lower in CKO forelimbs than in CKO hind limbs, showing that differential timing of POR deletion still has an effect at E13.5. These data show that POR inactivation led to cholesterol deficiency in CKO forelimbs. Further measurements in 2-month-old mice showed that, in CKO forelimbs, cholesterol was still reduced (87.3% in CKO mice compared to 92.9% in controls), whereas the precursor lathosterol had accumulated (12.7% for CKO mice versus 7.1% in controls), although the overall amounts of sterols were similar (CKO, 2.83 ± 0.36 mg of sterol extracted/g of extracted oil; control, 2.50 ± 0.54 mg/g).

We tried to rescue the forelimb phenotype by manipulating the diet of dams, feeding them either a VAD diet to counter retinoic acid excess, a diet supplemented with 2% cholesterol to counter cholesterol deficiency, or a combination of both diets. Examination of forelimbs of CKO embryos from dams on either cholesterol supplemented or combined diet showed that soft tissue webbing was less obvious particularly at E14.5 (Fig. 9D and data not shown [compare to Fig. 4F, inset]). In contrast, on a VAD diet, soft tissue webbing and splaying of digits 3 and 4 was still pronounced (data not shown). These data are consistent with the involvement of cholesterol deficiency in soft tissue syndactyly in CKO forelimbs.

DISCUSSION

We have shown that POR is required for normal development of the limb and its skeleton. POR deficiency in humans...
causes disordered steroidogenesis and occasionally bone malformations resembling Antley-Bixler syndrome (27). By knocking out POR specifically in limb bud mesenchyme in the embryo, we were able to reproduce most skeletal malformations seen in systemic POR deficiency seen in patients, such as abnormal bowing of long bones, joint contractures, ankylosis, and digital abnormalities (11, 34), with some of these features being more prominent postnatally. We saw some aspects such as digital abnormalities in only the forelimbs of CKO embryos although other features were seen in both forelimbs and hind limbs. The reason for this difference is that POR deletion occurs at an earlier stage in development and is more efficient in the forelimbs than in the hind limbs using Prx-Cre, as has been reported previously (49). Since the forelimb phenotype has more of the features seen in POR deficiency in human patients, we concentrated on analyzing the development of the forelimbs at the molecular level. Overall, our results demonstrate the importance of cellular metabolism and a local functioning P450 system in the limb throughout development.

**P450 pathways operating in limb development.** Our microarray data showed that the digital plate of the developing mouse forelimb expresses P450 enzymes participating in retinoic acid, cholesterol, and arachidonic acid metabolism in addition to metabolizing chemical compounds; expression of nine of these, involving the same metabolic pathways, was also detected in whole E11 mouse embryos by reverse transcription-PCR (13). It is known from many studies that retinoic acid metabolism and Cyp26 enzymes play major roles in embryogenesis, limb development, and patterning (52, 55, 61, 62, 70, 96), and the general relevance of cholesterol metabolism for embryogenesis has also been well established (42, 89). In contrast, although arachidonic acid metabolism is known to contain cytochrome P450-regulated steps (9, 10) and its products have been implicated in vascular homeostasis and angiogenesis (5, 26), little is known about the function of this pathway in embryonic development. Thus, although Cyp enzymes involved in arachidonic acid metabolism are expressed in the digital plate of the forelimb, it is not clear whether inactivation of this
pathway contributes to the defects. Some cytochrome P450s from the Cyp2 family have been highlighted as potentially interesting in a developmental context because they generate cis-epoxyeicosatrienoic acids, which regulate a range of cellular processes (78). Thus, for example, Cyp2c29, one of the P450s we found to be expressed in the digital plate of the forelimb, generates 14,15-cis-epoxyeicosatrienoic acid, which has been shown to release a potent mitogenic growth factor in epithelial cell lines (12).

The importance of P450-dependent pathways downstream of POR which metabolize retinoic acid and cholesterol was confirmed by our biochemical analyses in developing limbs. In CKO mouse forelimbs, POR protein was markedly reduced at E10.5 and may have already begun to impair activity of P450 enzymes. As a consequence, by E12.5 to E13.5, the retinoic acid levels were markedly increased in CKO forelimbs, while the cholesterol levels were decreased. In CKO hind limbs, POR protein was still just detectable at E11.5 and retinoic acid levels had not increased by E12.5 and, although cholesterol levels were lower in CKO hind limbs at E13.5 compared to wild-type limbs, this decrease was not as marked as in CKO forelimbs.

The microarrays of CKO forelimbs at E12.5 showed changes in the expression of a cohort of genes involved in both retinoic acid and cholesterol pathways. These expression changes are indicative of metabolic feedback loops being used in order to compensate for retinoic acid excess and cholesterol deficiency, respectively (19, 73). It is striking that a microarray performed on the brain tissue of a cholesterol-deficient mouse (88) resulted in an upregulation of genes involved in cholesterol synthesis and cellular uptake, as well as a downregulation of Abca1 (sterol efflux), very much like our results. We also found SREBP-2 to be upregulated, which directly induces transcription of genes involved in cholesterol synthesis and uptake (40).

Lipid metabolism, in particular sterol levels, continued to be disturbed during the postnatal life of CKO mice. Two-month-old CKO mice had accumulated substantial amounts of lipid in the forepaws and still showed an unbalanced ratio in sterols. This shows that local dysfunctional metabolism cannot be compensated for by an intact liver even after birth. Further investigations will be needed to clarify whether, and to what extent, these changes in the limbs of 2-month-old animals are a direct consequence of embryonic cholesterol deficiency.

**Contribution of metabolic pathways to forelimb defects.** Elevated retinoic acid levels might cause the stunted growth of the distal part of the forelimb in POR-deficient mice and contribute to the patterning defects in the wrist and digits. It has been well established that the effects of excess retinoic acid on proximo-distal patterning depend on the time of embryo exposure, with earlier exposure reducing proximal elements and later exposure reducing distal elements (47). If retinoic acid levels are continuously elevated from the very beginning, then all parts of the limb should be more or less equally affected, as, for example, by functionally inactivating the retinoic acid-metabolizing enzyme Cyp26b1 (96). Thus, the relatively late increase in retinoic acid in Pnx1-Cre; PORlox/lox forelimbs seems consistent with defects in wrist and digits while the failure to rescue syndactyly with the VAD diet makes it unlikely that excess retinoic acid makes a significant contribution to this aspect of the phenotype. How retinoic acid might cause the patterning defects is not clear because, for example, no changes in Hox gene expression were seen even in clearly malformed limbs. It might be significant that the expression of FoxC1, a gene encoding a transcription factor, shown to be upregulated in CKO forelimb buds in our microarray experiment, was enhanced particularly in the wrist region, a site of one of these pattern defects. FoxC1 has been shown to respond directly to retinoic acid (53), and changes in its expression have been reported in DiGeorge syndrome (95), which is associated with defects in retinoic acid homeostasis. Interestingly, FoxC1 has been linked to skeletal development (68) and mesodermal cell fate choice (91), but since its function has not yet been studied in limb development its potential contribution to the phenotype will require further investigation.

Cholesterol deficiency is clearly implicated in soft tissue syndactyly and the defective development of skeletal primordia in CKO forelimbs. Thus, for example, drug-induced cholesterol deficiency in rats leads to remarkably similar defects, including a wide space between digits 3 and 4 and even down to changes in the detailed expression of genes such as Ihh in developing digits (32). The fact that a high-cholesterol diet only slightly ameliorated the phenotype of CKO mice may be explained by the difficulty of passing on the full amount of cholesterol from dam to embryo since cholesterol has to be actively transported via the placenta (92).

The proximate cause of syndactyly in CKO forelimbs appears to be the reduction of interdigital Mxs2 expression, as shown by in situ hybridization experiments and microarrays. Mxs2 normally coincides with interdigital apoptosis during limb development (24), but in Pnx1-Cre; PORlox/lox limb buds it is reduced except between digits 3 and 4, although why this space is spared is not clear. Interestingly, enzymes of cholesterol biosynthesis are regionally restricted in their expression during normal digital morphogenesis, e.g., HMG-CoA reductase expression becomes confined to interdigital zones which undergo apoptosis at E12.5 (48).

The CKO limb phenotype has features in common with human syndromes known to be caused by mutations in cholesterol-synthesizing enzymes (37, 45, 85) and with the related mouse models, even though these are all systemic disorders, whereas our Pnx1-Cre; PORlox/lox mice have a strictly peripheral deficiency. Thus, for example, patients with Smith-Lemli-Opitz Syndrome, caused by a mutation in 7-Dehydrocholesterol reductase, often show 2,3 toe syndactyly in addition to postaxial polydactyly (17), while patients with mutations in either Desmosterol reductase (25), Emopamil binding protein, or NADH steroid dehydrogenase-like (CHILD syndrome or X-linked dominant chondrodysplasia punctata [38, 44]) or Lamin B receptor (90) have short limbs. In some cases, the related mouse model has no limb defects like the Desmosterolosis model but, in others, the mice have a wider range of limb abnormalities, including shortening, soft tissue syndactyly, and polydactyly (44, 89).

It has been proposed that the basis for limb defects seen under conditions of cholesterol deficiency is due to perturbation of Hedgehog signaling because cholesterol modification of Hedgehog proteins has been shown to affect signaling range and efficiency (reviewed in references 21, 30, and 50) and because Sonic hedgehog (Shh) and Indian hedgehog (Ihh) are critical for limb patterning and skeletogenesis (8, 87, 97).
Gofflot et al. (32) suggested that syndactyly of anterior digits in rat embryos after treatment with a cholesterol inhibitor arises because this part of the limb bud fails to expand normally due to changes in the range of Shh. However, in Ptx1-Cre; PORlox/lox limb buds, there is syndactyly of both anterior and posterior digits, and the changes in cholesterol levels may occur too late to affect Shh signaling. Therefore, syndactyly may be due to perturbed Ihh activity, which would also explain the reduction in longitudinal growth of the skeletal elements in the limb (77). We examined the expression of two genes, Patched1 and Gli1, which are known to be transcriptionally regulated by Hedgehog signaling and often used as reporters of hedgehog responding cells, in E13.5 forelimbs (see Fig. S1A to D in the supplemental material). Both expression patterns were slightly changed compared to control embryos, but this may be due to altered Ihh expression in CKO limbs (see Fig. 5H) rather than a change in the range of Ihh signaling.

It is intriguing that Hedgehog activity has been shown to be influenced by metabolites of all three P450 pathways (2, 16, 41, 42), identified three P450 pathways that operate in developing limb tissue (78). Following the developmentally active molecules in embryos (78). Following the suggestion about the basis for fetal alcohol syndrome (20), we speculate that some Cyp enzymes may have higher affinities for xenobiotic compounds than for their endogenous substrates. Thus, an excess of xenobiotic compounds during embryogenesis may keep the P450 system occupied and thereby distract it from metabolizing endogenous compounds. This could then lead to accumulation of endogenous substrates and deficiency of products, both of which could be manifested in disease or malformation.

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