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Citation for published version:
https://doi.org/10.1371/journal.pgen.1002711

Digital Object Identifier (DOI):
10.1371/journal.pgen.1002711

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
PLoS Genetics

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Prdm5 Regulates Collagen Gene Transcription by Association with RNA Polymerase II in Developing Bone

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Abstract

PRDM family members are transcriptional regulators involved in tissue specific differentiation. PRDM5 has been reported to predominantly repress transcription, but a characterization of its molecular functions in a relevant biological context is lacking. We demonstrate here that Prdm5 is highly expressed in developing bones; and, by genome-wide mapping of Prdm5 occupancy in pre-osteoblastic cells, we uncover a novel and unique role for Prdm5 in targeting all mouse collagen genes as well as several SLRP proteoglycan genes. In particular, we show that Prdm5 controls both Collagen I transcription and fibrillogenesis by binding inside the Col1a1 gene body and maintaining RNA polymerase II occupancy. In vivo, Prdm5 loss results in delayed ossification involving a pronounced impairment in the assembly of fibrillar collagens. Collectively, our results define a novel role for Prdm5 in sustaining the transcriptional program necessary to the proper assembly of osteoblastic extracellular matrix.


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Funding: Work in the authors’ laboratory was supported by the Danish National Research Foundation, the Danish National Advanced Technology Foundation, the Novo Nordisk Foundation, the EC FP7 programs (ONCOMIRS, grant agreement number 201102, and APO-SYS: This publication reflects only the authors’ views. The commission is not liable for any use that may be made of the information herein., the Lundbeck Foundation, and the Danish Cancer Society. This work has also been funded by the German Federal Ministry of Education and Research to the German Mouse Clinic (NGFPluus grant No. 01GS0850), Infrarentier grant No. 01KX1012, and by an EU grant (EUMODIC, LSFG-2006-037188, German Mouse Clinic) and the Wellcome Trust (senior research fellowship to JR 084229, centre core grants 077707 and 092076, and instrument grant 091020). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

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Introduction

PRDM proteins constitute a family of transcriptional regulators characterized by the presence of a N-terminal PR- domain that shares 20–30% similarity to the SET domain of histone methyltransferases and a variable number of zinc-finger domains typically involved in protein-DNA or protein-protein interaction [1]. Members of this family influence tissue specific differentiation as demonstrated for Prdm1 in lymphoid cell maturation [2], and Prdm16 in brown fat development [3]. Moreover, several members of the family are deregulated in pathological settings, most notably cancer, by acting either as oncogenes or tumor suppressors [1].

PRDM5 localizes to human chromosome 4q26 and encodes, aside from the PR domain, 16 C2H2 zinc fingers. PRDM5 has previously been reported to lack intrinsic histone methyltransferase activity but to predominantly repress transcription by recruiting G9a and HDACs enzymes to target genes [4]. Furthermore, PRDM5 has been indicated as a potential tumor suppressor in various cancers [5–7], but its role in mammalian development and normal physiology has not been addressed. In zebrafish, Prdm5 loss induces morphogenetic defects due to impairment of convergent extension movements at the gastrulation stage, likely resulting from deregulation of the WNT inhibitor Dkk1 [8]. Recently, mutations in PRDM5 were detected in Brittle Cornea Syndrome (BCS) [9], a connective tissues disease characterized by thinning of the cornea and a wide spectrum of additional symptoms including dermal and skeletal defects [10].

Bone is composed of a highly specialized, mineralized collagenous matrix that provides tensile strength to the skeletal system. Collagen I is the major component of osteoblasts matrix, composed of a heterotopic triple helix derived from Col1a1 and Col1a2 chains typically in a 2:1 stoichiometric ratio [11,12]. Approximately 40 collagen genes are annotated in mammalian genomes encoding around 28 proteins and, of these, type I collagen is part of the subfamily of fibrillar collagens [13]. Collagen chains are synthesized and assembled as triple helical procollagen molecules. Extracellular proteinase cleavage of N- and...
Embryonic glycosan from the Small Leucine Repeat family (SLRP), such as further assembled into fibrils and fibers [14]. This process is C-terminal telopeptides leads to mature tropocollagen that is essential for both the chondrogenic and osteogenic programs [23]. A number of transcription factors are known to be key regulators of expression of a multitude of extracellular matrix (ECM) genes associated with bone development, such as Runx2 [22], which controls the activity of the Collagen and SLRP gene families. Interestingly, Prdm5 predominantly binds exonic regions of collagen genes and associates with RNA Polymerase II to sustain Collagen I transcription.

C-terminal telopeptides leads to mature tropocollagen that is further assembled into fibrils and fibers [14]. The latter process is regulated by other extracellular macromolecules including proteoglycans from the Small Leucine Repeat family (SLRP), such as Decorin and Fibrinmodulin [15,16].

A number of transcription factors have been discovered as regulators of collagen I genes (reviewed in [17,18]), such as Sp1 [19], CebpB [20] or members of the AP1 family [21]. Furthermore, a number of transcription factors are known to be key regulators of bone development, such as Runx2 [22], which controls the expression of a multitude of extracellular matrix (ECM) genes essential for both the chondrogenic and osteogenic programs [23].

We present here a novel molecular function for Prdm5 in sustaining transcription of key ECM genes. Prdm5 is highly expressed in the osteoblast region of developing bones in vivo and genome wide mapping of Prdm5 occupancy in osteoblastic cells identifies all collagens and a number of SLRP genes as direct targets for Prdm5. Interestingly, Prdm5 binds predominantly within the exonic regions of collagen genes and its presence dictates the amount of intragenic RNA polymerase II. Indeed, Prdm5 sustains transcription of Collagen I genes by maintaining RNA polymerase II occupancy throughout the ColIa1 gene, while the binding to a distal enhancer element upstream of Decorin gene suggests a further role in chromatin organization. Osteoblasts lacking Prdm5 display decreased Collagen I and Decorin expression leading to reduced Collagen I fiber assembly in vivo. Downregulation of these key extracellular matrix genes likely participates in the delayed ossification and decreased bone mineral density observed in Prdm5 mutant mice. Our data defines novel roles for Prdm5 as a transcriptional modulator of collagen genes by influencing RNA polymerase II occupancy, as well by binding to enhancer-like elements in osteoblastic cells.

Results

Prdm5 is expressed in developing bones of mouse embryos

To address a possible role in mammalian development for Prdm5, a gene-trap mouse model featuring the integration of a β-galactosidase-neomycin (β-geo) cassette in intron 2 of the Prdm5 gene was generated (Prdm5<sub>geo</sub>). This cassette is preceded by a splice acceptor site to direct exon 2-β-geo splicing and ends with a poly-A site to terminate transcription (Figure 1A). In mutant cells, expression of the Prdm5 locus results in the production of a fusion transcript between the first two exons of Prdm5 (860 amino acids) and the β-geo cassette with a resulting fusion protein of approximately 135 kDa in size (Figure S1A). To validate the effectiveness of the gene-trap system, we quantified the levels of the wt Prdm5 allele in Prdm5<sub>geo</sub>LacZ/LacZ embryonic fibroblasts and found it to reach a maximum of 10% relative to the expression in wt littermates (Figure S1A). In adult organs, except for brain, testis and lung, we observed Prdm5 levels reduction to be at least 85% in the tissues tested (Figure S1B). In contrast to the essential role in zebrafish [8], Prdm5<sub>geo</sub>LacZ/LacZ mice are viable and fertile and the mutant allele segregates according to Mendelian ratios (Figure S1C).

To characterize the expression pattern of Prdm5, we tracked the β-galactosidase expression driven by the endogenous Prdm5 promoter by whole mount X-gal staining at various developmental stages. At E10.5–12.5 the LacZ reporter was expressed in a diffuse staining pattern along meso-endodermal derived regions with higher intensity in the heart (Figure 1B and 1C). At E14.5 LacZ staining accumulated in limbs and snout regions and in particular in cartilaginous templates (Figure 1D). From E16.5 a specific staining pattern was observed in skeletal elements, particularly in long bones and ribs (Figure 1E). In these tissues LacZ was highly expressed in the osteoblastic regions including the trabecular compartment and periosteum/perichondrium (arrows in Figure 1F). LacZ staining on sections from E16.5 embryo tibia revealed that the Prdm5 promoter is active in a subpopulation of cells in the osteoblast region (periosteum and trabecular area) (Figure 1G), whereas no signal was detected in the hypertrophic or proliferative chondrocytes zones (Figure 1G). Moreover, LacZ staining of calvariae of Prdm5<sub>geo</sub>LacZ/LacZ mice at P0 indicated that Prdm5 expression in osteoblasts is not restricted to long bones but can be detected also in skull sutures and weakly in calvariae (Figure 1H). Robust PRDM5 expression in osteoblasts was further confirmed in primary human osteoblast cells isolated from healthy donors, compared to a panel of human immortalized cell lines of different origins (Figure S1E). Moreover we found comparable Prdm5 expression levels in mouse primary calvarial osteoblasts, the osteoblastic MC3T3 cell line and primary embryonic fibroblasts (Figure S1F). In summary, in vivo expression analyses confirmed Prdm5 as consistently expressed in osteoblastic compartments in the mouse.

Acute Prdm5 deregulation affects osteogenic differentiation in vitro

Since Prdm5 is highly expressed in osteoblastic cells, we chose the MC3T3 cell line model to investigate the roles of Prdm5 during osteogenic differentiation. Cells were transduced with lentiviral shRNA constructs against Prdm5, which resulted in efficient reduction of both Prdm5 transcript and protein levels (Figure 2A). Prdm5 depletion did not significantly affect proliferation of MC3T3 cells as assessed by BrdU labeling (data not shown) but led to a significant reduction in matrix mineralization as measured by Alizarin red staining of calcium nodules upon induction of osteogenic differentiation (Figure 2B). In line with this, overexpression of PRDM5 induced the opposite phenotype resulting in increased nodule formation (Figure 2C and 2D). In parallel, the
significance of Prdm5 in chondrogenesis was evaluated by knocking down Prdm5 in the ATDC5 chondrogenic cell line (Figure S2A). In this system, Prdm5 loss did not affect chondrogenic differentiation, as evaluated by measuring glycosaminoglycan deposition (Figure S2B).

To investigate transcriptional changes imposed by Prdm5 loss in primary osteoblasts, expression levels of a series of osteogenic markers in Prdm5 wild type and mutant calvarial osteoblasts were measured by qRT-PCR. Significant reduction was observed for transcripts encoding Osteocalcin (Bglap1) and Bone sialoprotein (Ibsp), both late osteoblast markers, while transcript levels for early markers such as Osteopontin (Spp1), Osterix (Sp7) and Runx2 were unchanged (Figure 2E). When assayed for mineralization activity, no difference in matrix calcification was detected by Alizarin red staining in calvarial osteoblasts from cohorts of WT and mutant animals (Figure S2C and S2D). However, this phenotype may depend on cellular adaptation in culture, since treatment of wild type calvarial osteoblasts with a siRNA oligo which efficiently reduces Prdm5 levels, resulted in decreased matrix mineralization after 14 days of osteogenic stimulation (Figure S2E).

Collectively, the data indicate that Prdm5 exerts a cell-autonomous function in the osteogenic pathway.

Prdm5 targets gene bodies of transcriptionally active genes via a consensus sequence

To unveil the molecular functions of Prdm5 in osteoblastic cells and identify direct target genes, chromatin immunoprecipitation followed by deep sequencing (ChIP-seq) was performed for Prdm5 in the MC3T3 cell line.

Two different Prdm5 polyclonal antibodies were generated and western blot analysis of Prdm5 wild type and mutant mouse embryonic fibroblasts revealed that these antibodies recognize distinct epitopes (Figure S3A), and both were confirmed as suitable for ChIP experiments (Figure S3B).

Data from ChIP-seq analyses with the two antibodies were overlaid resulting in 1712 common loci we defined as high confidence Prdm5 target regions (Figure S3C and Table S1). Interestingly, 29% of Prdm5 peaks resided in promoter regions, while 39% of the peaks resided inside the body of genes (Figure 3A). Across all genes, Prdm5 binding was distributed throughout the length of target genes with the highest density around the TSSs (Figure 3B). A de novo motif finding algorithm for Prdm5 peak centers identified a putative consensus sequence for Prdm5 binding (Figure 3C). This sequence bears strong similarity to a Prdm5 consensus previously identified by in vitro random
Figure 2. Prdm5 deregulation impairs osteogenic differentiation in vitro. A) Upper panel. qRT-PCR of Prdm5 levels in MC3T3 cells transduced with lentiviral shRNA constructs against Prdm5 (shPrdm5-a and shPrdm5-b) and control construct. Lower panel. Prdm5 western blot from the same experiment. Tubulin is included as loading control. B) Upper panel. Quantification of Alizarin red staining after 21 days of osteogenic differentiation in MC3T3 cells. Data are presented as mean of 3 independent experiments ± SEM. ** = p < 0.01 and *** = p < 0.005 (t-test). Lower panel. Representative image from osteogenic differentiation experiments. C) Western blot showing overexpression of human PRDM5 (marked with star) in MC3T3 cells (filled circle = endogenous Prdm5). GFP overexpression is used as a negative control and Vinculin western blot for equal protein loading. D) Quantification of Alizarin red staining from osteogenic differentiation experiments of MC3T3 cells overexpressing GFP or PRDM5. A representative experiment is shown and data are presented as average ± standard deviation. E) qRT-PCR analysis of WT and Prdm5LacZ/LacZ calvaria osteoblasts for
Figure 3. Analyses of Prdm5 chromatin interactions. A) Diagram illustrating the overall distribution of Prdm5 binding sites categorized according to the distance from the nearest TSS (see Text S1). B) The mean distribution of tags across gene bodies for Prdm5 ChIP-seq (Prdm5-ab1 in blue, Prdm5-ab2 in red and IgG in black). Vertical dashed line at x = 0 represents the TSS. Positions after the TSS are represented as % of the length of the gene. C) Upper panel. Slogos plot produced using the motifs detected by the Weeder program from Prdm5 “shrunk” peaks (see Text S1). Lower panel. DNA pulldown assay from nuclear extract of 293 cells overexpressing HA-PRDM5 using biotinylated oligos representing the Col1a1 exon 33 (WT) and a mutated control sequence (G-A/T Mut). D) Histogram showing the percentage of H3K9me3 (left panel), H3K4me3 (middle panel) and RNA Polymerase II (right panel) positivity for “Random sampling” (mean value of 100 iterations for 1446 random genes sets) or for Prdm5 target genes. E) Q-Q plot comparing the quantile distribution of Prdm5 target genes’ expression (on Y axis) and all genes (on X axis). Red line is reference line representing equal quantile distribution.

doi:10.1371/journal.pgen.1002711.g003
Figure 4. Prdm5 targets all collagen genes and regulates type I collagen expression. A) ChiP-qPCR validation of Prdm5 peaks in collagen genes or negative control regions from an independent chromatin preparation immunoprecipitated with IgG, Prdm5-Ab1 (in black and blue respectively, plotted on left Y axis) or Prdm5-Ab2 (in red, plotted on right Y axis). Orange horizontal line represents the highest "noise" value obtained by ChiP-qPCR on a set of negative regions. B) Biological processes enrichment from gene ontology annotation of Prdm5 target regions. C) Distribution of the "peak centre" position for collagen genes targeted by Prdm5 or random sampling of Prdm5 target genes according to genetic feature. D) Correlation between Prdm5-Ab1 coverage inside the gene body of all mouse collagen genes (X-axis) and Pol II coverage in the same regions (Y-axis) normalized by base pairs. E) qRT-PCR for Prdm5, Col1a1, and Col1a2 in MC3T3 cells treated for 72 hours with siRNA oligos against Prdm5 (siPrdm5-1 and -2) or controls. Results are presented as average of four independent experiments ± SD; * = p<0.05, ** = p<0.01. F) Upper panel. ChiP-qPCR for RNA Pol II in WT and mutant (blue and red respectively) calvarial osteoblasts along the Col1a1 gene. IgG control is represented by black and green lines respectively. X-axis = distance (in bp) from Col1a1 TSS, * = p<0.05 (unpaired t-test). Lower panel. Genome browser snapshot of the corresponding Col1a1 genomic region displaying MC3T3 tracks for: qPCR amplicons, IgG, RNA Pol II and Prdm5-Ab1 coverage. G) Western blot from co-immunoprecipitation experiment of HA-PRDM5 in HEK293 cells; endogenous interacting proteins or IgG are indicated. doi:10.1371/journal.pgen.1002711.g004
exclusively in the gene body with approx. 60% of peaks centered in exonic regions (Figure 4C). Importantly, Prdm5 occupancy in the body of collagen genes correlated with the amount of bound RNA polymerase II in the same regions (Figure 4D), suggesting a role for Prdm5 in sustaining transcriptional activity of the collagen gene family.

Very high enrichment for Prdm5 binding was observed in the two genomic loci corresponding to the collagen I genes Col1a1 and Col1a2 (Figure 4D and Figure S4C). Prdm5 knockdown by means of two siRNA oligos demonstrated that Prdm5 occupancy in Col1a1 and Col1a2 genes was functionally relevant, as reduction in Prdm5 levels led to a decrease in transcript and protein levels of both type I collagen genes (Figure 4E and Figure S4D). This effect was observed also in primary osteoblasts upon genetic ablation of Prdm5 (Figure S4E). Given the close correlation between Prdm5 occupancy and RNA polymerase II presence, we measured the occupancy of the latter along the whole length of the Col1a1 gene in Prdm5 wild type and mutant osteoblasts. While RNA polymerase II levels were unchanged in LacZ/LacZ cells at the Col1a1 TSS, we observed a significant drop in RNA polymerase II levels in mutant Prdm5 osteoblasts between +6.2 kb and the end of the Col1a1 gene (Figure 4F). Towards understanding the mechanism, we hypothesized that Prdm5 could affect RNA polymerase II by direct interaction. Indeed, overexpressed HA-PRDM5 co-immunoprecipitated with endogenous RNA polymerase II and with higher affinity to the elongating form of RNA polymerase II as evident from analysis using a phospho-serine 2 specific RNA polymerase II antibody (Figure 4G). In summary, Prdm5 targets virtually all the collagen genes in the mouse genome and high Prdm5 occupancy inside the Col1a1 gene body promotes RNA polymerase II occupancy and transcription.

Prdm5 regulates Decorin via a distal element with an enhancer-like chromatin signature

Analyses of the annotation of Prdm5 bound loci revealed that the Prdm5 target repertoire extends to genomic regions encoding other ECM genes involved in collagen fibrillogenesis, such as Periostin (Psmb) and genes from the SLRP family, such as Decorin (Den), Fibromodulin (Fmod), Biglycan (Bgn) and Epiphycan (Epc). Also in this case, Prdm5 occupancy on selected targets was validated in independent samples from MC3T3 cells (Figure 5A), as well as primary calvarial osteoblasts (Figure S5A and S5B).

Since Decorin is well known to regulate collagen fibrillogenesis, we analyzed the influence of Prdm5 on Decorin expression. Indeed, we observed that Prdm5 knockdown resulted in decreased Decorin transcription (Figure 5B). This effect could be reproduced in Prdm5LacZ/LacZ calvarial osteoblasts (Figure 5C). While cell-associated Decorin protein levels were only mildly decreased upon Prdm5 knockdown (Figure 5D), the amount of secreted Decorin detected in cell culture media from Prdm5 siRNA treated cells was strongly reduced (Figure 5D). A closer inspection revealed that the Prdm5 binding site assigned to Decorin gene was 100 kilobases distant from its TSS, suggesting the binding to a distal enhancer (Figure S5C). Chromatin immunoprecipitation for H3K27ac and H3K4me1 and H3K27ac confirmed that Prdm5 bound a site upstream of Den with a chromatin signature corresponding to an enhancer element (Figure 5E). Our data show that Prdm5 targets SLRP family members and likely regulates Decorin via a distal enhancer.

Delayed ossification and impairment of collagen fibrillogenesis in Prdm5LacZ/LacZ embryos

Collagen I is the main component of osteoblastic ECM [11] and Decorin is known to regulate collagen I fibrillogenesis [16]. The observed Prdm5 regulation of Collagen I and Decorin genes prompted us to characterize their deregulation in vivo and the resulting phenotype in Prdm5LacZ/LacZ mice. qRT-PCR analyses revealed that the Col1a1 and Col1a2 transcripts were significantly reduced upon Prdm5 loss in E16.5 limbs (Figure S6A). Moreover, decreased Collagen I was observed by in situ hybridization in the periostium at E16.5 (data not shown), as well as by immunofluorescence microscopy (Figure 6A). While Decorin transcript levels were unchanged in whole E16.5 mutant limbs (Figure S6B), immunofluorescence staining displayed reduction of Decorin protein, particularly in the periostium and invading osteoblasts region (Figure 6A), indicating an osteoblast-restricted Prdm5 regulation of Decorin. Given that both molecules are involved in collagen fiber formation, fibrillar collagen levels were evaluated in Prdm5LacZ/LacZ embryonic limbs by picrosirius red staining. Using bright field microscopy, a decreased staining of collagen could be appreciated in the mutants (Figure S6C). Moreover, using polarized light to visualize specifically assembled collagen fiber birefringency, a marked decrease in the presence and organization of collagen fibers was observed in Prdm5LacZ/LacZ embryonic limbs (Figure 6A).

Histological examination revealed a shorter osteoblast compartment in mutant animals (Figure 6B), suggesting a delay in the ossification process. Likewise, Von Kossa stainings revealed decreased calcification in mutant limbs further pointing to an impaired ossification process in Prdm5 mutants (Figure 6C). To quantitate the delayed ossification, wild type and Prdm5LacZ/LacZ mice E18.5 embryos were analyzed by micro-CT (μCT) scanning. Quantification of total bone volume demonstrated a significant reduction in the ossification process in mutant embryos (Figure 6D). However, at E16.5, no overt differences in the expression of various bone formation markers were observed (Figure S6D). To measure the impact of the embryonic ossification defect in young mice hind limbs from cohorts of WT and Prdm5LacZ/LacZ mice of both genders were analyzed by peripheral Quantitative Computed Tomography (pQCT). Images of distal metaphyseal sections from CT-scans of femurs at 5 weeks of age demonstrated a decrease in bone mineral density (Figure 6E). Quantification of total bone mineral density, total mineral content and total bone area in large cohorts of mice demonstrated a statistically significant reduction in all three parameters in Prdm5LacZ/LacZ mice of both genders (Figure 6F and Table S2). Separate measurements of the cortical and trabecular compartments revealed a more robust reduction in all measured parameters in cortical regions than trabecular areas (Table S2), coinciding with the areas where downregulation of Collagen I and Decorin was predominantly observed in mutant embryo limbs.

In summary, Prdm5LacZ/LacZ animals display a significant reduction in collagen levels and fibrillogenesis, likely resulting in the observed osteopenic phenotype.

Discussion

In this study, we uncover a novel function for Prdm5 in promoting the transcription of key extracellular matrix genes in osteoblastic cells. We find that Prdm5 is specifically expressed in the osteoblastic compartment of developing bones and exerts its function along the osteogenic lineage by promoting osteogenic differentiation in culture. Mechanistically, we demonstrate that Prdm5 targets ECM gene families such as collagens and small leucine-rich proteoglycans. By association with RNA polymerase II, Prdm5 sustains the transcription of collagen I genes, while the regulation of Decorin expression is mediated via binding to a distal enhancer-like element. Prdm5 regulation of these genes occurs in
Figure 5. Prdm5 regulates Decorin through a distal enhancer. A) ChIP-qPCR validation of Prdm5 peaks on selected ECM genes or negative regions from an independent sample immunoprecipitated with IgG, Prdm5-Ab1 (in black and blue respectively, plotted on left Y axis) or Prdm5-Ab2 (in red, plotted on right Y axis). Orange horizontal line represents the highest “noise” value obtained by ChIP-qPCR on a set of negative regions. B) qRT-PCR analysis of Decorin transcript (Dcn) levels upon Prdm5 knockdown as in Figure 4E. Results are presented as average of four independent experiments ±/− SD; * = p<0.05. (C) qPCR analysis of WT and Prdm5<sub>LacZ/LacZ</sub> calvarial osteoblasts for Decorin. Expression values were normalized to the control WT samples. * = p<0.05; T-test, (+/+ n = 14, LacZ/LacZ n = 19 clones). D) Upper panels. Western blot analysis of Decorin levels upon Prdm5 knockdown in cell layers; Tubulin is used as loading control. Lower panels. Western blot analyses of purified proteoglycans from cell culture media from knockdown cells. Tubulin is used as purity control and Fibronectin for equal protein loading. E) ChIP-qPCR with indicated antibodies for Prdm5 binding site upstream of Dcn gene. Meg3 TSS region is used as negative control.

doi:10.1371/journal.pgen.1002711.g005
Prdm5 Promotes the Transcription of ECM Genes

A

Collagen I

B

+/

LacZ/LacZ

Decom

C

+/

LacZ/LacZ

Procollagen 1 red

D

Relative BV/TV

1.2

1.1

1.0

0.9

0.8

0.7

E

pQCT-scan

F

Total density (mg/cm²)

550

500

450

400

350

300

250

+/

LacZ/LacZ

+/

LacZ/LacZ

Males

Females

***
vivo in developing limbs resulting in the decreased bone mineral density observed in Prdm5LacZ/LacZ animals.

Members of the PRDM family display tissue-specific patterns of expression [24], in agreement with a role in tissue-specific differentiation. In line with this, Prdm1 is known to be a master regulator of lymphoid differentiation [2], Prdm16 to control brown fat development [3], Prdm14 to regulate embryonic stem cell pluripotency and germ cell differentiation [25,26] and Prdm9 to determine meiotic recombination hotspots [27]. So far Prdm5 has not been characterized in the context of mammalian development. Our study thus provides the first evidence of a role for Prdm5 in tissue-specific differentiation extending the concept of PRDM proteins as regulators of specific tissues and in agreement with the idea of functional specialization of PRDM members during expansion of the family in vertebrates [28].

The identification of high Prdm5 expression in osteoblasts and its function in osteogenic differentiation in vivo permitted us to evaluate its molecular functions in a relevant cellular context. Indeed, it is noteworthy that Prdm5 silencing does not restrict chondrogenic differentiation in vitro suggesting cell type specificity in Prdm5 action.

By genome wide mapping of Prdm5 binding sites in a pre-osteoblastic cell line, we demonstrate a unique capacity of Prdm5 to bind the whole family of collagen genes and especially to bind these genes within the gene body. This is an unprecedented feature for a transcriptional regulator, i.e. binding the gene bodies of all the members of such a large gene family. Moreover, we observed Prdm5 occupancy in genomic regions encoding for non-collagen proteins with collagenous domains (e.g. C1q family), suggesting that either Prdm5 consensus sequence is overrepresented in genomic regions encoding for collagenous domains, or that simply Prdm5 binds common regulatory elements shared by specific gene families. Indeed we detected Prdm5 binding to several members of the SLRP family as well as a number of genes encoding for essential extracellular matrix components (complete list in Table S1), demonstrating that Prdm5 potentially regulates a wide but specific transcriptional program necessary for proper extracellular matrix formation.

In this study, we focus on fibrillar collagens, particularly Collagen I genes; these were highly enriched for Prdm5 binding and are essential constituent of osteoblastic matrix. A number of transcription factors have been shown to regulate Collagen I genes and the location of their binding sites on Col1a1 and Col1a2 promoters have been shown to determine the expression in different osteoblast subtypes [29,30]. Very little is known concerning the regulation of Col1a1 and Col1a2 gene expression by factors binding downstream of their promoter, except for a repressor region located within intron 1 that can recruit GATA and IRF proteins to block enhancer stimulation of promoter activity [31,32]. To our knowledge, Prdm5 is the first example of a transcriptional modulator able to bind a consensus sequence found inside collagen genes, particularly Col1a1 and Col1a2.

Interestingly, upon Prdm5 loss in osteoblasts, we observe decreased RNA polymerase II occupancy throughout the gene body of the Col1a1 gene, while at the TSS, RNA polymerase II occupancy remains unchanged. This suggests that Prdm5 is sustaining transcription of the Col1a1 gene by affecting polymerase processivity. This hypothesis is further supported by the observed interaction between Prdm5 and RNA polymerase II. The higher enrichment for the processive, “elongating”, form of RNA polymerase II phosphorylated on Serine 2 of its C-terminal domain, argues in favor of Prdm5 directly sustaining RNA polymerase II processivity although further analyses are required to clearly define the underlying mechanism. Since Prdm5 binds predominantly exonic regions of collagen genes, and splicing is known to occur co-transcriptionally [33], there may be a role for Prdm5 in the coupling of splicing to transcription. However, we failed to detect an altered Col1a1 splice pattern in Prdm5 mutant osteoblasts (data not shown), making this hypothesis less likely. The correlation between Prdm5 binding levels within collagen genes and RNA polymerase II occupancy suggests that Prdm5 in certain contexts may act as a transcriptional activator in contrast to the previously described role of PRDM5 acting predominantly as a transcriptional repressor [4]. Interestingly, we observe major enrichment for Prdm5 target genes to be transcriptionally active, presenting both H3K4me3 and RNA Polymerase II (Figure 3D), suggesting a predominant role for Prdm5 in transcriptional activation in osteoblasts.

The Prdm5 target repertoire extends also to SLRP genes, including Decorin (Den), Fibromodulin (Fmod), Biglycan (Bgi) and Epiphycan (Epc). Members of this family are involved in correct type I collagen fibers assembly [15]. Specifically, we found a Prdm5 binding site residing 100 kb upstream of the Den TSS. Decorin is the closest gene within a range of 760 kb and the Prdm5 binding site displays the chromatin signature of an enhancer element, suggesting a previously undiscovered role for Prdm5 in transcriptional enhancement or chromatin organization. Decorin has been shown to bind directly collagen I [34] and, in bone tissues, mice lacking Decorin display decreased collagen fiber diameter, although they do not show pronounced skeletal defects [35]. Our data show a marked decrease in fibrillar collagen staining, as evaluated by collagen fibers birefringency, indicating that downregulation of both Collagen I transcripts as well as Decorin might contribute to the skeletal phenotype observed.

Of direct relevance, mutations in PRDM5 were recently detected in Brittle Cornea Syndrome [9]. Brittle Cornea Syndrome is a generalized connective tissue disease characterized by impairment of ECM formation and patients develop a number of other symptoms, aside from ocular defects, such as skin hyperelasticity, joint hypermobility and skeletal defects [10,36]. While no studies so far have causally linked PRDM5 to this disease, our data demonstrating that Prdm5 regulates the expression of fibrillar collagens are in line with the defects in ECM production and assembly characteristically observed in BCS patients. The distinct expression pattern observed for Prdm5 in developing skeleton prompted us to evaluate a bone phenotype but future studies will be needed to understand if Prdm5LacZ/LacZ mice develop also corneal, skin and joint defects resembling BGS or
Prdm5 Promotes the Transcription of ECM Genes

Materials and Methods

Animal experiments

To generate the Prdm5LacZ strain, ES cell clone AV0702 from the Sanger Institute Gene Trap project was microinjected into C57BL/6 blastocysts. The integration site of the β-gal cassette was established using long range PCR with primers spanning different regions of intron 2 and a genotyping strategy was devised accordingly. All experiments were performed on mice backcrossed for at least 6 generations into the C57BL/6 strain and comparisons between WT and mutant animals always refer to littermates. All animal experimentation was performed with approval from Danish authorities (Dyreforsøgstilsynet, protocol number 2006/562-43) and the Regierung von Oberbayern (Government of Upper Bavaria).

Histological staining and immunohistochemistry

For whole mount X-gal staining, embryos were deskinned (after E15) and fixed in 0.25% glutaraldehyde (Sigma). Stainings were performed by incubation in staining solution containing 0.02% NP40, 0.01% Sodium Deoxycholic acid, 2 mM MgCl2, 20 mM Tris-HCl (pH 7.4), 50 μM K-Ferroycyanide, 50 μM K-Ferricyanide, 1 mg/ml X-gal in PBS (chemicals purchased from Sigma). Stained embryos were post-fixed in 4% paraformaldehyde and cleared in increasing concentrations of glycerol in 1% KOH. Images were acquired with a Leica D-Lux 3 on Leica S6D stereoScope. Von Kossa staining was performed by staining dehydrated sections in 1% AgNO3 under UV light, followed by incubation with 5% Sodium thiosulfate. Picrosirius red stainings were performed as described [38]. Images were acquired with a Leica D-Lux 3 on Leica S6D stereoScope. For whole mount X-gal staining, embryos were deskinned (after E15) and fixed in 0.25% glutaraldehyde (Sigma). Stainings were performed by incubation in staining solution containing 0.02% NP40, 0.01% Sodium Deoxycholic acid, 2 mM MgCl2, 20 mM Tris-HCl (pH 7.4), 50 μM K-Ferroycyanide, 50 μM K-Ferricyanide, 1 mg/ml X-gal in PBS (chemicals purchased from Sigma). Stained embryos were post-fixed in 4% paraformaldehyde and cleared in increasing concentrations of glycerol in 1% KOH. Images were acquired with a Leica D-Lux 3 on Leica S6D stereoScope. Von Kossa staining was performed by staining dehydrated sections in 1% AgNO3 under UV light, followed by incubation with 5% Sodium thiosulfate. Picrosirius red stainings were performed as described [38]. Images were acquired with a Leica D-Lux 3 on Leica S6D stereoScope.

Cell culture and transfections

Primary human osteoblasts (kindly provided by Bente Langdahl, Århus University, Denmark) were isolated from bone biopsies of healthy donors. MC3T3 cells were maintained in Alpha-MEM (Gibco) with 10% FBS (HyClone) and 1% penicillin-streptomycin (Gibco). ATDC5 cells were maintained in DMEM/F12 (Gibco) media supplemented with 5% FBS, 10 μg/ml human transferrin (Roche) and 30 nM sodium selenite (Sigma). Calvarial osteoblasts were derived as previously described [21]. Differentiation protocols and transfection/transduction techniques are detailed in Text S1.

Co-immunoprecipitation, immunoblotting, and gene expression analyses

For co-immunoprecipitation experiments HEK293 cells were transfected with indicated plasmids and, 48 hours after, lysed in E18.5 embryos were scanned using a micro CT scanner (model 1172, Skyscan, Belgium) at 50 kV, 200 μA and a 0.5 mm aluminum filter. Adult mice at 5 weeks of age were analyzed by pQCT using Stratec XCT Research SA (Stratec Medizintechnik GmbH, Germany) at the German Mouse Clinic [39]. Analyses details are provided in Text S1.

Supporting Information

Figure S1 Prdm5LacZ/LacZ mice do not display gross abnormalities and PRDM5 is expressed in osteoblasts. A) Left panel. Western blot of +/+ and LacZ/LacZ mouse embryo fibroblasts using serum from mice immunized with recombinant Prdm5-1-142. Right panel. qPCR analysis for Prdm5 wt and Prdm5-LacZ fusion alleles in mouse embryo fibroblasts of the three genotypes. B) qPCR for Prdm5 wild type transcript in a panel of tissues from wild type and Prdm5LacZ/LacZ mice. Results are shown as the average of 3 animals per group ± standard deviations. C) Number of mice obtained at weaning with different genotypes from Prdm5LacZ/LacZ intercrosses. In parenthesis the expected numbers according to Mendelian ratios. Statistical differences were calculated by Chi-square test. D) Weight of wild type and Prdm5LacZ/LacZ mice up to 56 weeks of age. E) qPCR analysis for PRDM5 in primary human osteoblasts from 6 different donors (black bars) and a panel of human immortalized cell lines of different origins (grey bars). F) Western blot analysis of Prdm5 protein expression in the indicated mouse cell lines. *= unspecific bands for equal loading.

Figure S2 Prdm5 knockdown affects osteogenic differentiation in vitro, but not chondrogenic differentiation. A) Left panel. qPCR of Prdm5 levels in chondrogenic ATDC5 cells infected with lentiviral shRNA constructs against the Prdm5 transcript (shPrdm5-a) and control construct. Right panel. Western blot measuring Prdm5 protein levels in the same cells. Actin is used as a control for equal protein loading.

For whole cells lystate immunoblotting, cells were harvested and lysed in RIPA buffer and subjected to standard SDS-PAGE. Protocols and antibodies used are detailed in Text S1.

Chromatin immunoprecipitation and Deep sequencing

Chromatin immunoprecipitation assay (ChiP) protocol and antibodies used are detailed in Text S1. Libraries for sequencing were obtained using the ChiP-seq DNA sample prep kit (Illumina) according to manufacturer recommendations and samples were sequenced on a Genome Analyzer II sequencer (Illumina). Primers for ChiP-qPCR experiments are listed in Table S3.

Bioinformatic analysis

Microarray and ChiP-seq analyses are detailed in Text S1.

μCT and Peripheral quantitative computed tomography

E18.5 embryos were scanned using a micro CT scanner (model 1172, Skyscan, Belgium) at 50 kV, 200 μA and a 0.5 mm aluminum filter. Adult mice at 5 weeks of age were analyzed by pQCT using Stratec XCT Research SA+ (Stratec Medizintechnik GmbH, Germany) at the German Mouse Clinic [39]. Analyses details are provided in Text S1.

Histological staining and immunohistochemistry

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of glycosaminoglycans deposition from ATDC5 cells infected with control or shPrdm5-a constructs after 17 days of stimulation with chondrogenic media and stained with Alcian blue. Data are presented as the mean of 2 independent experiments ± standard deviation. Lower panel. Representative picture from the chondrogenic differentiation experiment. C) Representative pictures of alizarin red stained WT and Prdm5LacZ/LacZ calvarial osteoblasts after 14 days of osteogenic differentiation. D) Quantification of the alizarin red staining from osteogenic differentiation experiments in WT and Prdm5LacZ/LacZ calvarial osteoblasts. Data are presented as mean ± standard deviation for 10 different littermate primary cultures per group. E) Left panel. Western blot measuring Prdm5 protein levels in primary calvarial osteoblasts treated for 72 hours with control oligo or siRNA pool against Prdm5 (siPrdm5). Vinculin is used as a control for equal protein loading. Right panel. Quantification of calcified matrix deposition from calvarial osteoblasts treated with control or siPrdm5 after 14 days of stimulation with osteogenic media and stained with Alizarin red. Data are presented as the mean of 4 independent experiments ± standard deviation. Lower panel. Representative picture from the osteogenic differentiation experiment.

**Figure S3** Validation of Prdm5 ChIP-grade antibodies. A) Western blot of +/- and LacZ/LacZ mouse embryo fibroblasts using Prdm5 rabbit polyclonal antibodies Prdm5-ab1 and Prdm5-ab2. B) Left panel. Transfection control of HEK293 cells containing a stably integrated GAL4TkLuc reporter with empty vector or vector expressing Prdm5 fused to Gal4 DNA binding domain (Gal4BD-Prdm5 OE). Tubulin is used for equal protein loading. Right panel. Chromatin immunoprecipitation from Gal4BD-Prdm5-OE sample with IgG (negative control), Gal4 (positive control) and a range of in-house generated or commercially available Prdm5 antibodies. C) Venn diagram of the overlap of peaks identified by ChIP-seq in MC3T3 in experiment either with Prdm5-ab1 or Prdm5-ab2. D) Slogo representation of re-analysis of sequences retrieved by previously published random oligonucleotide experiment [4].

**Figure S4** Prdm5 binds inside Col1a1 and Col1a2 gene bodies and regulates their transcription. A) ChIP-qPCR in primary calvarial osteoblasts with IgG or Prdm5-ab1 (black and red bars respectively) for Prdm5 binding site in selected collagen genes. Genomic regions around Meg3 and Sona5b are used as negative controls. Orange horizontal line represents the highest “noise” value obtained by ChIP-qPCR on a set of negative regions. B) ChIP-qPCR in wild type (red bars) and Prdm5LacZ/LacZ (blue bars) calvarial osteoblasts for a number of collagen genes. Genomic regions around Meg3 and Sona5b are used as negative controls. Orange horizontal line represents the highest “noise” value obtained by ChIP-qPCR on a set of negative regions. C) Genome browser snapshot for Col1a1 (upper panel) and Col1a2 (lower panel) regions. Tracks represent IgG, Prdm5-ab1 and Prdm5-ab2 sequencing results as indicated. D) Western blot for Prdm5 and Collagen I levels from MC3T3 cells treated for 72 hours with control or Prdm5 siRNA oligos. Tubulin is used for equal protein loading. E) qPCR analysis of WT and Prdm5LacZ/LacZ calvarial osteoblasts for Col1a1 and Col1a2. Expression values were normalized to WT controls. *** = p<0.001 according to T-test, (+/- n = 14, LacZ/LacZ, n = 19 clones).

**Figure S5** Prdm5 binds a distal element from Dna gene TSS in calvarial osteoblasts. A) ChIP-qPCR in primary calvarial osteoblasts with IgG or Prdm5-ab1 (black and red bars respectively) for Prdm5 binding site assigned to ECM genes identified from ChIP-seq. Genomic region around AdamTS9 is used as negative control. Orange horizontal line represents the highest “noise” value obtained by ChIP-qPCR on a set of negative regions. B) ChIP-qPCR in wild type (red bars) and Prdm5LacZ/LacZ (blue bars) calvarial osteoblasts for the main peaks assigned to ECM genes identified from ChIP-seq. Genomic region around AdamTS9 is used as negative control. Orange horizontal line represents the highest “noise” value obtained by ChIP-qPCR on a set of negative regions. C) Genome browser snapshot for Prdm5 target region assigned to Dna gene. Tracks represent IgG, PCR, Prdm5-ab1 and Prdm5-ab2 sequencing results as indicated.

**Figure S6** Characterization of Prdm5 target genes levels and osteoblasts markers in Prdm5LacZ/LacZ E16.5 limbs. A) qPCR analysis for Col1a1 and Col1a2 in E16.5 wild type and Prdm5LacZ/LacZ limbs (n = 4). * = p<0.05. B) qPCR analysis for Dna in E16.5 WT and Prdm5LacZ/LacZ limbs (n = 4). C) Bright field image of picrosirius red staining in wild type and Prdm5LacZ/LacZ E16.5 tibia. D) In-situ hybridizations for Spp1/Osteopontin and Ibsp (bar = 400 um) and immunofluorescence micrographs of Mmp13 (bar = 100 µm), Vegfa and Osterix (bar = 200 µm) in WT and Prdm5LacZ/LacZ E16.5 embryonic femurs or tibiae. White arrow indicates growth plate direction for orientation. All histological analyses are performed on parallel sections between littermate embryos of same sex.

**Table S1** Genomic regions identified as high confidence Prdm5 targets from ChIP-seq experiment. Assigned ensembl gene IDs by annotation are indicated.

**Table S2** pQCT parameters measured in wild type and Prdm5LacZ/LacZ animals at 5 weeks. P-value by T-test is indicated and cells color-coded according to: yellow = p<0.05, orange = p<0.01, red = p<0.005.

**Table S3** Primers used for qPCR and ChIP-qPCR throughout the study.

**Text S1** Extended description of experimental procedures including bioinformatics analyses and supplemental references.

**Acknowledgements**

We thank Klaus Hansen, Kristian Helin, and Erwin Wagner for critical reading of the manuscript. We would like to thank Fengqin Jia for mouse genotyping; Reinhard Seelig, Susanne Wittich, and Anja Wohlrab and the GMC animal caretaker team for expert technical help; and Flavia de Lima Alves for technical assistance with proteomic analysis.

**Author Contributions**

Conceived and designed the experiments: GGG RAC JRC AHL. Performed the experiments: GGG KHdL MW BM CKF KTJ JR WH LC. Analyzed the data: GGG KHdL LC HAM. Author Contributions: GGG KHdL MW BM CKF KTJ JR WH HAM. Wrote the paper: GGG JRC AHL.
References


