Targeted Deletion of the Metastasis-Associated Phosphatase Ptp4a3 (PRL-3) Suppresses Murine Colon Cancer

Mark W. Zimmerman1, Gregg E. Homanics1,2, John S. Lazo1,3,9

1 Department of Pharmacology and Chemical Biology, University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania, United States of America, 2 Department of Anesthesiology, University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania, United States of America, 3 Department of Pharmacology, University of Virginia School of Medicine, Charlottesville, Virginia, United States of America

Abstract

Ptp4a3 (commonly known as PRL-3) is an enigmatic member of the Ptp4a family of prenylated protein tyrosine phosphatases that are highly expressed in many human cancers. Despite strong correlations with tumor metastasis and poor patient prognosis, there is very limited understanding of this gene family’s role in malignancy. Therefore, we created a gene-targeted murine knockout model for Ptp4a3, the most widely studied Ptp4a family member. Mice deficient for Ptp4a3 were grossly normal. Fewer homozygous-null males were observed at weaning, however, and they maintained a decreased body mass. Although Ptp4a3 is normally associated with late-stage cancer and metastasis, we observed increased Ptp4a3 expression in the colon of wildtype mice immediately following treatment with the carcinogen azoxymethane. To investigate the role of Ptp4a3 in malignancy, we used the most commonly studied murine colitis-associated colon cancer model. Wildtype mice treated with azoxymethane and dextran sodium sulfate developed approximately 7–10 tumors per mouse in the distal colon. The resulting tumor tissue had 4-fold more Ptp4a3 mRNA relative to normal colon epithelium and increased PTP4A3 protein. Ptp4a3-null mice developed 50% fewer colon tumors than wildtype mice after exposure to azoxymethane and dextran sodium sulfate. Tumors from the Ptp4a3-null mice had elevated levels of both IGF1Rβ and c-MYC compared to tumors replete with Ptp4a3, suggesting an enhanced cell signaling pathway engagement in the absence of the phosphatase. These results provide the first definitive evidence implicating Ptp4a3 in colon tumorigenesis and highlight the potential value of the phosphatase as a therapeutic target for early stage malignant disease.

Introduction

Protein tyrosine phosphatase-4a3 (Ptp4a3), along with Ptp4a1 and Ptp4a2, comprise the 4a-family of protein tyrosine phosphatases. This modest gene family is commonly referred to as the phosphatases of regenerating liver (PRL), due to the discovery of Ptp4a1 in the regenerating liver cells of mice following partial hepatectomy [1]. The significant homology (>75% amino acid identity) found among Ptp4a family members may denote similar enzymology but all three family members are conserved throughout mammalian species, suggesting non-redundant biological roles for each. The in vivo properties and functions of these enigmatic phosphatases remain poorly understood.

Interest in Ptp4a3 can be attributed to its significant potential as a biomarker and as a therapeutic target for malignant cancers. Many human cancers express high PTP4A3 levels including tumors of the colon [2], breast [3], ovary [4], liver [5], stomach [6], and stroma [7], and elevated PTP4A3 expression often correlates with increased tumor invasiveness and poor prognosis [8]. Additionally, ectopic PTP4A3 overexpression enhances tumor cell migration and invasion in vitro [9]. While definitive evidence is lacking, Ptp4a3 has been proposed to modulate multiple signaling pathways involving SRC [10], Rho GTPases [9], and PI3K-Akt [11] in various forms of cancer. The complexity of the pathway alterations seen when Ptp4a3 is overexpressed may also reflect its ability to act as a phosphatidylinositol 5-phosphatase [12]. No reports have conclusively demonstrated a role for Ptp4a3 in the physiology of normal cells or tissues.

Azoxymethane (AOM) is a procarcinogen that when metabolized in the colon is mutagenic and drives tumorigenesis. AOM in combination with the inflammatory agent dextran sodium sulfate (DSS) produces a widely-used murine model that faithfully replicates colon malignancies driven by chronic inflammatory conditions such as ulcerative colitis [13]. Several signaling pathways are implicated in the pathogenesis of AOM-induced colon cancer including KRAS [14], β-Catenin [15], c-MYC [16], Insulin-like Growth Factor-1 Receptor β (IGF1Rβ) [17], and Transforming Growth Factor β (TGFβ) [18]. Interestingly, Ptp4a3 has been identified as a direct regulatory target of TGFβ signaling in colon cancer [19].
In the current study, we used a gene-targeting approach to generate mice lacking Ptp4a3 and interrogate the potential role of Ptp4a3 in colon tumorigenesis. AOM exposure acutely increased Ptp4a3 expression in the colon. Ptp4a3-null mice were resistant to colon tumorigenesis implicating this gene in the pathogenesis of malignant disease. Moreover, tumors derived from Ptp4a3-null mice overexpressed the cancer associated IGF1Rβ and c-MYC suggesting involvement of these oncogenic signaling pathways.

Figure 1. Gene-targeting the Ptp4a3 locus. A) The Ptp4a3 floxed allele was created by inserting loxP sites (red arrowheads) around exon 2. This mutation resulted in the disruption of a HindIII sequence that increases the size of the DNA fragment produced by restriction digest from 5.6 to 10.2 kb. Following expression of Cre recombinase, the sequence between the loxP sites is removed leaving a single loxP site and decreasing the size of the restriction fragment to 6.4 kb. This mutation results in deletion of the initiation codon causing a frameshift mutation producing a nonfunctional protein product. B) Southern blot analysis of genomic DNA was used to monitor these genetic changes and genotype mice containing the wildtype, floxed, or knockout alleles. Each lane is from an individual mouse. C) Quantitative RT-PCR analysis on total mRNA from fetal heart tissue revealed no change in Ptp4a1 and Ptp4a2 mRNA levels while Ptp4a3 was reduced and not detectable in heterozygous and homozygous-null tissue, respectively. (* = p < 0.05; n = 4/genotype). D) The PTP4A3 protein product was detectable by western blot in whole protein lysates from wildtype and heterozygous fetal heart tissue, but not in homozygous Ptp4a3-null samples.

doi:10.1371/journal.pone.0058300.g001
PTP4A3 (Fig. 1D). Aside from the aforementioned phenotypic observations, mice without functional Ptp4a3 appeared grossly normal relative to wildtype littermates.

Expression and knockout of Ptp4a3 in mouse tissues

Because the expression of endogenous PTP4A3 protein in normal tissues has not been well characterized, we examined tissue protein samples from wildtype and Ptp4a3-null mice. First, we assayed several tissue types for PTP4A3 protein expression by Western blot (Fig. 3). Fetal heart, fetal intestine, adult heart, skeletal muscle, pancreas, lung, spleen, brain, thymus, colon, and small intestine all expressed detectable levels of PTP4A3 in contrast to the liver and kidney, which had no detectable PTP4A3 protein. These results also confirm the efficacy of the global gene deletion approach, as no PTP4A3 protein was detectable in any of the livers from Ptp4a3-null mice. Histological analysis was also performed on wildtype and Ptp4a3-null tissue samples (Fig. S4). Upon examining multiple tissue types, no overt abnormalities were observed and all samples appeared qualitatively normal.

Ptp4a3 expression increases immediately following AOM exposure

Since low levels of PTP4A3 were detectable in the normal colon epithelium, we assayed Ptp4a3 gene expression immediately following treatment with the intestinal procarcinogen AOM (12.5 mg/kg) or saline control in wildtype C57BL/6j mice. Mice were sacrificed 8 and 24 hr after AOM injection and colon epithelial cells were collected for analysis. Total mRNA was isolated and quantitative RT-PCR was performed to assay for Ptp4a3 gene expression levels. Interestingly, Ptp4a3 was upregulated by 78% at 8 hr and 60% at 24 hr in AOM-treated epithelial relative to control (Fig 2C). Protein lysates from AOM treated mice suggest that the PTP4A3 protein levels are also increased in these tissues (Fig. 2D). While the role of Ptp4a3 in colon cancer is traditionally thought to involve late-stage tumors and metastasis, this finding suggests a potential role in early-stage disease and tumorigenesis.

Knockout of Ptp4a3 suppresses intestinal tumor formation

To explore a potential functional role for Ptp4a3 in tumor formation, we subjected mice to a widely used AOM-DSS model of colitis-associated colon cancer. Wildtype and Ptp4a3–null mice were injected with a single dose of AOM (12.5 mg/kg) followed by three cycles of 2.5% DSS consumption (Fig. 2A). This model produces distinct histological changes relative to normal controls, including inflammation corresponding to DSS treatment, and

Table 1. Genotype distribution of Ptp4a3 mutant mice.

| Offspring genotype at weaning | Male | Female | n | $X^2$ | p  |
|-----------------------------|------|--------|---|--------|----|
| Male                        |      |        |   |        |    |
| $+/+$                       | 75   | 70     | 240| 6.23   | <0.05|
| $+/-$                       | 117  | 127    | 276| 2.34   | N.S.|
| $-/-$                       | 48   | 79     | 69 |        |    |
| Female                      |      |        |   |        |    |
| $+/+$                       | 60   | 69     | 120| 0.72   | N.S.|
| $+/-$                       | 120  | 138    | 60 |        |    |
| $-/-$                       | 60   | 69     | 240| 6.23   | <0.05|

There was a observed decrease in number of male Ptp4a3-null mice observed at weaning relative to the expected amount predicted by Mendelian genetics (p<0.05). Female mice of each genotype were born at the expected frequency (1:2:1).

doi:10.1371/journal.pone.0058300.t001

Results

Creation of Ptp4a3 mutant mice

We disrupted the Ptp4a3 genomic locus using the Cre-lox system of site-specific recombination based on the position of two inserted loxP sites (Fig. 1A and further detail in Fig. S1). Mutant mice were backcrossed to the C57BL/6j strain for at least five generations. The knockout allele was created by crossing Ptp4a3floxed mice with transgenic mice expressing CRE-recombinase driven from a general promoter (EIIA) to recombine the target site and create global knockout mice [20]. Insertion of the 3’ loxP site destroyed an endogenous HindIII site increasing the size of the genomic DNA fragment produced by restriction digest from 5.6 to 10.2 kb. Subsequent deletion of the target sequence reduced the restriction fragment size from 10.2 to 6.4 kb. Distinct band sizes corresponding to each allele are observed when analyzed by Southern blot hybridization with a ~300 bp probe corresponding to exon 6 (Fig. 1B).

An analysis of >500 pups that were produced by heterozygous mating pairs indicated all potential genotypes were observed in the resulting offspring. While females were observed at the expected Mendelian ratios, we noted a significant decrease (p<0.05) in the number of Ptp4a3-null males at weaning relative to the predicted frequency (Table 1). Given this finding, it is possible that knockout males either possessed a survival disadvantage or that Ptp4a3-null germ cells had a preconception phenotype. Ptp4a3-null male mice exhibited an approximate 10% decrease in body mass (p<0.003) and 7% decrease in body mass index (p<0.004) compared to wildtype littermates at 6 wk of age (Fig. S2). This phenotype also appeared to be confined to male mice as female Ptp4a3-null mice did not exhibit a significant decrease in body mass or body mass index.

Because fetal heart tissue had been previously suggested to have high levels of Ptp4a3 expression [21], we next performed quantitative RT-PCR on total RNA samples from fetal heart tissue (E19.5) to determine the relative mRNA levels of Ptp4a1, Ptp4a2, and Ptp4a3. While Ptp4a1 and Ptp4a2 levels remained similar between genotypes, Ptp4a3 mRNA was reduced in heterozygous tissue and not detectable in samples from Ptp4a3-null fetal heart tissue (Fig. 1C). Thus, compensation for Ptp4a3 loss by upregulation of either family members Ptp4a1 or Ptp4a2 at the mRNA level was excluded. Protein lysates from fetal heart tissue were assayed by Western blot for the presence of the PTP4A3 protein product. While detectable in samples from wildtype embryos, PTP4A3 was lower in lysates from heterozygous embryos and homozygous-null tissue contained no detectable PTP4A3 (Fig. 1D). Aside from the aforementioned phenotypic
subsequent dysplasia (Fig. 2B). Tumors were visually obvious in the distal colon of wildtype mice upon sacrifice at 12 or 16 wk after the initial AOM treatment and were (Fig. 2B and 3A). As indicated in Figure 3B, Ptp4a3-null mice exhibit a 54% decrease in tumor number ($p < 0.004$) following 16 wk of treatment. Although on average fewer tumors were observed at 12 wk in Ptp4a3-null mice relative to wildtype, this was not statistically significant ($p > 0.2$). Interestingly, the number of tumors ($p = 0.05$) as well as tumor diameter ($P < 0.001$) was significantly increased from 12 to 16 wk, while Ptp4a3-null tumors did not significantly increase in number or size. The average diameter of tumors produced by this model was 3–4 mm (Fig. 3C).

**Ptp4a3 is elevated in AOM-derived colon tumors**

Because high expression of PTP4A3 has been reported in human primary colon tumors [22], we examined Ptp4a3 expression in the mouse model of colon cancer. First, total mRNA was extracted from tumor tissue from wildtype mice and quantitative RT-PCR was used to assay for the expression level of each Ptp4a family member in normal colon and tumor tissue. Ptp4a3 was elevated 3.7-fold (**$p = 0.01$**), while Ptp4a1 and Ptp4a2 levels were significantly decreased (**$p = 0.0001$ and $p = 0.05$, respectively) ($n = 15$, bars = SEM). F) Western blot analysis demonstrating higher PTP4A3 protein levels in colon tumors compared to normal tissue. G) Western blot combined with qRT-PCR analysis also demonstrated that when comparing Ptp4a3 mRNA levels (listed above each lane) to PTP4A3 protein, high gene expression appeared to correspond to higher protein levels. doi:10.1371/journal.pone.0058300.g002

**Ptp4a3 Knockout Suppresses Colon Cancer**

Figure 2. *Ptp4a3* is expressed in AOM-DSS derived colon tumors and normal tissue. A) The AOM-DSS treatment paradigm used in this study features a single dose of AOM followed by 3 treatment cycles of DSS in the drinking water. B) Histological representation of normal colon tissue relative to tumor tissue demonstrates the efficacy of the AOM-DSS model. Following one cycle of DSS treatment, crypt dysplasia and mononuclear cell infiltration were apparent. Tumor tissue was present at both the 12 and 16 wk endpoints. Before sacrifice, mice were treated with BrdU for 4 hrs and cell proliferation was visualized by staining with a BrdU antibody. C) Quantitative RT-PCR was used to assay Ptp4a3 gene expression in normal colon epithelial tissue following treatment with either AOM or saline control. Ptp4a3 was elevated 73% in colon tissue following when measured 8 hr after injection and 60% at 24 hr (**$p < 0.001$; $n = 6$ treatment group; bars = SEM). D) Western blot of colon lysates indicated an increase in PTP4A3 protein following AOM exposure. E) Quantitative RT-PCR indicated changes in gene expression levels of Ptp4a family members in normal colon and tumor tissue. Ptp4a3 was elevated 3.7-fold (**$p = 0.01$), while Ptp4a1 and Ptp4a2 levels were significantly decreased (**$p < 0.001$ and $p < 0.05$, respectively) ($n = 15$, bars = SEM). F) Western blot analysis demonstrating higher PTP4A3 protein levels in colon tumors compared to normal tissue. G) Western blot combined with qRT-PCR analysis also demonstrated that when comparing *Ptp4a3* mRNA levels (listed above each lane) to PTP4A3 protein, high gene expression appeared to correspond to higher protein levels. doi:10.1371/journal.pone.0058300.g002
Loss of Ptp4a3 increases IGF1Rβ and c-MYC expression in tumors

We next examined lysates obtained from both wildtype and Ptp4a3-null colon tumors. We first used reverse phase protein array to assay the levels of over 130 different protein products contained in wildtype and Ptp4a3-null tumors (Fig S5). While protein levels in these tumors exhibited considerable heterogeneity, two known oncogenic signaling proteins, the receptor tyrosine kinase IGF1Rβ and the transcription factor c-MYC were expressed at higher levels in Ptp4a3-null tumors (Fig 4A). Following quantification, IGF1Rβ protein was on average 2.1-fold higher (p<0.001) and c-MYC was about 2.5-fold higher (p<0.02) in Ptp4a3-null relative to wildtype colon tumors (Fig 4B–C). In contrast, we did not observe a significant difference in AKT activation between genotypes (Fig 4D). This result suggests that tumors can potentially compensate for Ptp4a3 deficiency though altered signaling pathways.

Discussion

A number of genes have been implicated in the development and progression of colorectal cancer. Previous gene expression profiling studies identified 144 genes that are up-regulated in metastatic colorectal liver samples [2]. The only gene, however, that was consistently elevated in all of the metastatic samples was Ptp4a3. Both gene amplification and enhanced transcriptional activity are likely causal for the high levels. Despite the apparent importance of Ptp4a3 in tumor biology, our understanding of the functionality of Ptp4a3 is severely limited due in part to the absence of informative animal models. The gene targeted mouse model for disruption of the Ptp4a3 genomic locus that we have developed is useful not only for studying the phenotypic changes that occur with the global loss of the phosphatase, but also for future investigations on tissue and temporal specific gene deletion and collaborative interactions with other genes including the two other members of the Ptp4a family. Our model establishes that mice can survive in the absence of a functional Ptp4a3 gene, although there were a slightly lower number of male mice produced, and they are able to live to maturity under normal conditions without any major health deficiencies. This is in contrast to what has been reported with mice lacking the highly homologous Ptp4a2, which is thought to be the most ubiquitously expressed family member under normal conditions. Ptp4a2-null mice exhibited defective placental development and both genders showed retarded growth at embryonic and adult stages [23]. Ptp4a2 loss decreases the spongiosarcoma and decidua layers of the placenta impairing nutrient transport and causing embryonic growth retardation. Moreover, loss of Ptp4a2 results in AKT inactivation, which was not evident in our data regarding Ptp4a3 loss. Collectively, the differences in the two gene deletion models are consistent with non-overlapping functions of these two close phosphatase family members.

Deletion of PT34A3 protein was confirmed by Western blot analysis using a variety of tissue lysates from wildtype and Ptp4a3-null mice. Although initial studies had suggested Ptp4a3 expression was restricted to heart, skeletal muscle, and pancreas [24], our data revealed a more ubiquitous expression pattern. While the highest levels of PTP4A3 were observed in fetal heart, the protein was also detectable at lower levels in adult heart, skeletal muscle, spleen, pancreas, brain, lung, thymus, colon, and small intestine; no PTP4A3 protein was detectable the liver or kidney.

Because human PT4A3 has been implicated in the pathogenesis of human metastatic colorectal cancer, we investigated the effects of Ptp4a3 deletion in a mouse model of colon cancer. Treatment
with AOM/DSS is one of the most popular colon tumor mouse models and the C57BL/6J strain to which this model was backcrossed is particularly susceptible to colitis-associated cancer [13,16,17].

Ptp4a3 is traditionally classified as a gene associated with metastasis and not known to be involved in the early stages of cancer progression. In the current study, we provide evidence that the Ptp4a3 mRNA and PTP4A3 protein levels are increased soon after exposure to AOM, the initiating step in our colon cancer model. This is important evidence that PTP4A3 could be also involved in the preneoplastic stage of malignancy.

Mice subjected to the AOM/DSS model consistently developed tumors in the distal region of the colon. These primary tumors displayed consistently higher levels of Ptp4a3 relative to normal colon epithelium – similar to what is seen in human colon cancer patients [22]. Notably, mice deficient for Ptp4a3 had >50% reduction in tumor formation providing further evidence that PTP4A3 is a key mediator of colon cancer progression. Nevertheless, the complete absence of PTP4A3 phosphatase was insufficient to abolish colon tumorigenesis, suggesting that a subset of tumors may not require Ptp4a3 as a driver of the disease. This is supported by the finding that not all tumors in this model had high (>2-fold upregulation) Ptp4a3 expression levels.

The animal model we have developed presents a unique opportunity to address the role of Ptp4a3 in tumor biology. AOM exposure causes DNA damage and genotoxic stress. A prominent response to DNA damage is induction of p53, which can induce Ptp4a3 expression [25] and may provide an explanation for the induction of Ptp4a3 in the colon of AOM treated mice. Additionally, Ptp4a3 has been identified as a direct regulatory target of TGFβ signaling in colon cancer cells. The active TGFβ signal induces SMAD3/4 binding to the Ptp4a3 genomic locus and thus inhibition of gene transcription [19]. Loss of TGFβ is a frequently observed phenomenon in human colon cancer [26], as well as the AOM mouse model of colon cancer [18]. It is likely that this event contributes to elevated Ptp4a3 gene expression in cancer through SMAD3/4 inactivation. Interestingly, a mouse model deficient for Smad3 has been reported to spontaneously develop colon cancer [27], and Smad4 deficiency greatly exacerbates a mouse model of colon cancer [28]. The formation of neoplastic lesions in the Ptp4a3-null mice may be the consequence of the engagement of additional growth factor signaling pathways or oncogenes, such as IGF1Rβ and c-MYC. c-MYC is known to be increased in tumors after AOM/DSS treatment and both IGF1Rβ and c-MYC were markedly elevated in the Ptp4a3-null tumors relative to wildtype derived tumors.

Figure 4. Higher IGF1Rβ and c-MYC levels in Ptp4a3-null tumors. A) Cluster sample of the heatmap generated from RPPA analysis that was performed using colon tumor lysates from AOM-DSS treated wildtype and Ptp4a3-null mice. Protein targets were either higher (yellow), lower (blue), or unchanged (black). B) Protein levels were confirmed by western blot analysis colon tumor lysates from wildtype and Ptp4a3-null mice. IGF1Rβ and c-MYC protein were chosen because of they appeared to be the most consistently upregulated proteins in Ptp4a3-null samples. C) When quantified, IGF1Rβ protein levels were 2.1-fold higher in Ptp4a3-null tumors (p<0.001). D) c-MYC protein levels were 2.5-fold higher in Ptp4a3-null tumors (p<0.02). E) The levels of activated AKT, as indicated by phosphorylation of Ser473, were not significantly different by genotype relative to total AKT protein.

doi:10.1371/journal.pone.0058300.g004

The animal model we have developed presents a unique opportunity to address the role of Ptp4a3 in tumor biology. AOM exposure causes DNA damage and genotoxic stress. A prominent response to DNA damage is induction of p53, which can induce Ptp4a3 expression [25] and may provide an explanation for the induction of Ptp4a3 in the colon of AOM treated mice. Additionally, Ptp4a3 has been identified as a direct regulatory target of TGFβ signaling in colon cancer cells. The active TGFβ signal induces SMAD3/4 binding to the Ptp4a3 genomic locus and thus inhibition of gene transcription [19]. Loss of TGFβ is a frequently observed phenomenon in human colon cancer [26], as well as the AOM mouse model of colon cancer [18]. It is likely that this event contributes to elevated Ptp4a3 gene expression in cancer through SMAD3/4 inactivation. Interestingly, a mouse model deficient for Smad3 has been reported to spontaneously develop colon cancer [27], and Smad4 deficiency greatly exacerbates a mouse model of colon cancer [28]. The formation of neoplastic lesions in the Ptp4a3-null mice may be the consequence of the engagement of additional growth factor signaling pathways or oncogenes, such as IGF1Rβ and c-MYC. c-MYC is known to be increased in tumors after AOM/DSS treatment and both IGF1Rβ and c-MYC were markedly elevated in the Ptp4a3-null tumors relative to wildtype derived tumors.
While the Ptp4a3 gene product initially was thought to be involved in tumor metastasis and late stage disease, our results provide evidence for possible roles at other stages of the disease including pre-neoplastic transformation and early carcinogenesis. The concept of therapeutically targeting Ptp4a3 could therefore, be attractive at multiple stages of cancer.

Materials and Methods

Creation of Ptp4a3 mutant mice

The conditional gene-targeting vector was constructed using a phage-based E. coli recombination system [29]. Specific details regarding the vector construction and targeting strategy are described in Fig S1. We specifically targeted exon 2 because it contained the transcriptional start site and was necessary for proper translation of the mRNA transcript. Following transfection of the construct into R1 embryonic stem cells [30], mice were created from correctly targeted clones using standard chimeric animal production techniques with C57BL/6j blastocysts. The novel strain was backcrossed to C57BL/6J (The Jackson Laboratory) for >5 generations and mice for experiments were produced using heterozygous breeding pairs. Genotyping was performed by Southern blot analysis with a radiolabeled probe corresponding to ~300 bp of exon 6, which was external to the gene targeting vector. This study was carried out in accordance with the recommendations in the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health. All relevant protocols were approved by the Institutional Animal Care and Use Committee of the University of Pittsburgh.

AOM cancer model

Wildtype and Ptp4a3-null mice (male, 6–8 wks) were administered a single dose of AOM (12.5 mg/kg) (Sigma) in sterile saline by IP injection. DSS solution (2.5%) (MP Biomedicals) was given ad libitum for 7 d followed by 14 d of normal drinking water and this cycle was repeated a total of 3 times [13]. Experimental mice were euthanized at 12 or 16 wk following the initiation of treatment, at which point colon tissue was isolated, rinsed, and opened longitudinally for analysis. Tumor and normal tissue were snap frozen in liquid nitrogen or submerged in 10% neutral buffered formalin. For each mouse, individual tumors were counted and measured with a digital caliper and average tumor count and diameter were determined for each genotype.

Western blot analysis

Cells and tissues were lysed using RIPA buffer and quantified by Bradford assay. A total protein sample of 40 μg was separated using Novex SDS-PAGE reagents (Invitrogen) and transferred to nitrocellulose membranes. Membranes were blocked in Odyssey blocking buffer (LiCor Biosciences) and incubated with primary antibodies overnight followed by secondary fluorescent antibodies according to the manufacturers’ instructions. We used the following commercially available primary antibodies: PTP4A3 clone 318 (Santa Cruz Biotechnology), GAPDH, IGF1R, c-MYC, p-AKT(S473), and AKT (Cell Signaling Technology).

Quantitative RT-PCR

Total RNA was extracted from tissue using Trizol reagent as per the manufacturer’s protocol (Invitrogen). A total of 500 ng of mRNA was converted to cDNA using the iScript first strand synthesis kit (Bio-Rad). The primers (Table S1) used for target amplification were diluted to a final concentration of 500 pM, and real-time monitoring of the PCR reaction was performed on a Biorad IQ5 thermocycler with 2X Sybr Green Mastermix (Bio-Rad). The following program was run for 40 cycles: 95°C for 0:30; 58°C for 1:00; and 72°C for 0:30.

Reverse phase protein array

Protein lysates (100 μg each) from colon tumor samples (n = 5/genotype) were denatured and shipped frozen to MD Anderson Cancer Center (Houston, TX) for analysis. Briefly, lysates were two-fold serial diluted for 5 dilutions and arrayed on nitrocellulose-coated slides, probed with antibodies, and visualized by diaminobenzidine colorimetric reaction. Relative protein levels for each sample were determined by interpolation of each dilution curves from the standard curve antibody slide. All data points were normalized for protein loading and transformed to linear value. Linear values were transformed to Log2 value and then median-centered for hierarchical cluster analysis. The heatmap was generated in Cluster 3.0 as a hierarchical cluster using Pearson Correlation and a center metric (additional details are provided in Fig S5).

Statistics

Statistical analysis of offspring genotype was calculated by the Chi-squared test comparing observed and expected results. Data from cellular assays, western blot, and qRT-PCR quantifications was analyzed using the 2-tailed t-test. In both cases, significance was defined as p<0.05.

Supporting Information

Figure S1 (PDF)
Figure S2 (PDF)
Figure S3 (PDF)
Figure S4 (PDF)
Figure S5 (PDF)
Table S1 (PDF)

Acknowledgments

The authors would like to thank Carolyn Ferguson for her technical expertise and assistance.

Author Contributions

Conceived and designed the experiments: JSL GEH. Performed the experiments: MWZ. Analyzed the data: MWZ GEH JSL. Contributed reagents/materials/analysis tools: GEH JSL. Wrote the paper: MWZ GEH JSL.

Ptp4a3 Knockout Suppresses Colon Cancer

1. Diamond RH, Cressman DE, Laz TM, Abearns CS, Taub R (1994) PRL-1, a unique nuclear protein tyrosine phosphatase, affects cell growth. Mol Cell Biol 14: 3752–3762.

2. Saha S, Bardelli A, Buckhaults P, Velculescu VE, Rago C, et al. (2001) A phosphatase associated with metastasis of colorectal cancer. Science 294: 1341–1346.
5. Zhao WB, Li Y, Lin X, Zhang LY, Wang X (2008) Evaluation of PRL-3 expression, and its correlation with angiogenesis and invasion in hepatocellular carcinoma. J Mol Med 22: 187–192.

6. Ooki A, Yamashita K, Ikeuchi S, Sakuramoto S, Katada N, et al. (2011) Therapeutic potential of PRL-3 targeting and clinical significance of PRL-3 genomic amplification in gastric cancer. BMC Cancer 11.

7. Nieken TO, West RB, Linn SC, Alter O, Knowling MA, et al. (2002) Molecular characterisation of soft tissue tumours: a gene expression study. Lancet 359: 1301–1307.

8. Guzinská-Uszynowska K, Przybyź A (2011) PRL-3, an emerging marker of carcinogenesis, is strongly associated with poor prognosis. Anticancer Agents Med Chem 11: 99–108.

9. Foesselius JF, Keller PJ, Cox AD (2006) PRL tyrosine phosphatases regulate rho family GTPases to promote invasion and motility. Cancer Res 66: 3153–3164.

10. Liang F, Liang J, Wang WQ, Sun JP, Udho E, et al. (2007) PRL3 promotes cell invasion and proliferation by down-regulation of Csk leading to Src: activation. J Biol Chem 282: 5413–5419.

11. Wang H, Qaha SY, Dong JM, Maner E, Tang JP, et al. (2007) PRL-3 down-regulates PTEN expression and signals through PI3K to promote epithelial-mesenchymal transition. Cancer Res 67: 2922–2926.

12. McParland V, Varsano G, Li X, Thornton J, Baby J, et al. (2011) The metastasis-promoting phosphatase PRL-3 shows activity toward phosphoinositides. Biochemistry 50: 7579–7590.

13. Neufert C, Becker C, Neurath MF (2007) An inducible mouse model of colon carcinogenesis, is strongly associated with poor prognosis. Anticancer Agents Med Chem 11: 99–108.

14. O’Toole SM, Pegg AE, Swenberg JA (1993) Repair of O6-methylguanine and O4-methylthymidine in F344 rat liver following treatment with 1,2-dimethylhydrazine and O6-benzylguanine. Cancer Res 53: 3895–3898.

15. Neufert C, Becker C, Neurath MF (2007) An inducible mouse model of colon carcinogenesis, is strongly associated with poor prognosis. Anticancer Agents Med Chem 11: 99–108.

16. De Robertis M, Massi E, Poeta ML, Carotti S, Morini S, et al. (2011) The AOM/DSS animal model for the study of colon carcinogenesis: From pathways to diagnosis and therapy studies. J Carcinog 10.

17. Kamiengazi M, Mino-Kenudson M, Maraguchi E (2011) Animal models of colitis-associated carcinogenesis. J Biomed Biotechnol 2011.

18. Guda K, Claffey KP, Dong M, Nambar PR, Rosenberg DW (2003) Defective processing of the transforming growth factor-beta1 in azoxymethane-induced mouse colon tumors. Mol Carcinog 37: 51–59.

19. Jiang Y, Liu XQ, Rajput A, Geng L, Ongchin M, et al. (2011) Phosphatase PRL-3 is a direct regulatory target of TGFbeta in colon cancer metastasis. Cancer Res 71: 234–244.

20. Lakso M, Pichel JG, Gorman JR, Sauer B, Okamoto Y, et al. (1996) Efficient in vivo manipulation of mouse genomic sequences at the zygote stage. Proc Natl Acad Sci U S A 93: 5860–5865.

21. Guo K, Li J, Wang H, Osato M, Tang JP, et al. (2006) PRL-3 initiates tumor angiogenesis by recruiting endothelial cells in vitro and in vivo. Cancer Res 66: 9625–9633.

22. Mollevi DG, Aytes A, Paháles L, Marínez-Iniesta M, Baixeras N, et al. (2008) PRL-3 is essentially overexpressed in primary colorectal tumours and associates with tumour aggressiveness. Br J Cancer 99: 1718–1723.

23. Dong V, Zhang L, Zhang S, Bai Y, Chen H, et al. (2012) Phosphatase of regulating liver 2 (PRL2) is essential for placenta development by down-regulating PTEN (phosphatase and tensin homologue deleted on chromosome 10) and activating Akt. J Biol Chem (In press).

24. Matter WF, Eritilde T, Zhang C, Belagaje R, Stancato L, et al. (2008) Role of PRL-3, a human muscle-specific tyrosine phosphatase, in angiotensin-II signaling. Biochem Biophys Res Commun 383: 1061–1066.

25. Basak S, Jacobs SB, Krieg AJ, Pathak N, Zeng Q, et al. (2008) The metastasis-associated gene PRL-3 is a p53 target involved in cell-cycle regulation. Mol Cell 30: 303–314.

26. Massague J (2008) TGFβ in Cancer. Cell 134: 215–230.

27. Zhu Y, Richardson JA, Parada LF, Graff JM (1998) Sma3p mutant mice develop metastatic colorectal cancer. Cell 94: 703–714.

28. Takaku K, Oshima M, Miyoshi H, Masui M, Nelder MF, et al. (1998) Intestinal tumorigenesis in compound mutant mice of both Dpp4 (Sma3d4) and Apc genes. Cell 92: 645–656.

29. Liu P, Jenkins NA, Copeland NG (2003) A highly efficient recombineering-based method for generating conditional knockout mutations. Genome Res 13: 476–484.

30. Nagy A, Rossant J, Nagy R, Abramow-Newerly W, Rekai JC (1993) Derivation of completely cell culture-derived mice from early-passage embryonic stem cells, Proc Natl Acad Sci U S A 90: 8424–8428.
Table S1 - Primers used for quantitative RT-PCR. Listed are the forward and reverse primer sequences used to amplify each Ptp4a target gene as well as the Gapdh endogenous control.

| Target Gene | Forward Primer  | Reverse Primer          |
|-------------|-----------------|-------------------------|
| Ptp4a1      | CAACCAATGCGACCTTAA | CAATGGCATCGGCACCC       |
| Ptp4a2      | ATTTGCCATAATGAACCG | ACAGGAGCCTTCCCAAT       |
| Ptp4a3      | CTTCCCCATCACCACAACC | TACATGACGCAGCAGTCTGG    |
| Gapdh       | AACGACCCCTCTATTGAC | TCCACGACATACCTACGAC     |
SUPPLEMENTAL DATA

**Figure S1 – Strategy for targeting the Ptp4a3 gene locus.** A gene-targeting construct was created by retrieving a 9 kb fragment of murine strain 129X1 genomic DNA from a bacterial artificial chromosome (The Sanger Institute). The newly created targeting vector was transformed into *E. coli* and all cloning and recombination steps were performed in bacteria. First, a PGK driven neomycin resistance cassette (NEO) flanked by loxP sites (red arrows) was inserted between exons 1 and 2. Expression of CRE recombinase in these cells deleted the floxed region leaving behind a single loxP site. Next, a FRT flanked (orange arrows) PGK-NEO cassette adjacent to a single loxP site was inserted between exons 2 and 3. Following analysis by restriction digest and sequencing, this construct was electroporated into R1 embryonic stem cells (21). G418 and gancyclovir resistant ES cell clones were expanded and screened by Southern blot using a radio-labeled probe corresponding to ~300 bp of exon 6, which was external to the gene targeting vector. Correctly targeted clones were injected into C57BL/6J 3.5-day blastocysts and mice were created using standard chimeric animal production techniques. The NEO cassette was subsequently removed by crossing to a strain expressing FLPe recombinase from a general promoter (actin). The floxed allele was then crossed to a strain expressing CRE recombinase also from a general promoter (EIIA). The novel mutant strain was backcrossed to C57BL/6J (The Jackson Laboratory) for at least 5 generations and mice for experiments were produced using heterozygous breeding pairs.
**Figure S2** - *Male Ptp4a3 knockout mice exhibited decreased weight and body mass index.* A) When compared to wildtype littermates (n=9/genotype), male *Ptp4a3*⁺/⁻ mice exhibited an average of ~10% less body mass (p<0.005). B) Mice were also measured from the nose to the base of the tail and body mass index was determined (BMI=kg/m²). Male *Ptp4a3*⁺/⁻ littermates exhibited a ~7% decrease in BMI compared to wildtype (p<0.005). Neither of these phenotypes were significantly altered in female *Ptp4a3*⁺/⁻ mice compared to wildtype.
Figure S3 - Histological analysis of wildtype and Ptp4a3-null tissues. Freshly isolated tissues were submerged in 10% neutral buffered formalin (Sigma) and fixed at room temperature overnight. Tissues were dehydrated through an ethanol gradient, embedded in paraffin, and sectioned onto glass slides. Sections stained with hematoxylin and eosin appeared qualitatively similar between genotypes (bar=5 µm).
**Figure S4 - Expression and knockout of PTP4A3 in mouse tissues.** Western blot analysis was performed on whole organ lysates from adult wildtype mice (n=3) with Ptp4a3<sup>−/−</sup> lysates used as a negative control (n=1). We then assayed for expression of PTP4A3 protein in various mouse tissues with GAPDH as a loading control. While the highest levels of PTP4A3 were observed in lysates from fetal heart tissue, the protein was also detectable at lower levels in samples from adult heart, skeletal muscle, spleen, pancreas, brain, lung, thymus, colon, and small intestine. The liver and kidney were the only tissue types analyzed that exhibited little or no expression of PTP4A3 protein.
Figure S5 – Reverse phase protein array (RPPA) analysis. Protein lysates (100 ug each) from colon tumor samples (n=5/genotype) were denatured and shipped frozen to MD Andersen Cancer Center (Houston, TX) for analysis. Briefly, lysates were two-fold-serial diluted for 5 dilutions and arrayed on nitrocellulose-coated slides, probed with antibodies, and visualized by DAB colorimetric reaction. Relative protein levels for each sample were determined by interpolation of each dilution curves from the standard curve antibody slide. All the data points were normalized for protein loading and transformed to linear value. Linear values were transformed to Log2 value and then median-centered for hierarchical cluster analysis. The heatmap was generated in Cluster 3.0 as a hierarchical cluster using Pearson Correlation and a center metric.