

Inactivating Mutation in the Prostaglandin Transporter Gene, *SLCO2A1*, Associated with Familial Digital Clubbing, Colon Neoplasia, and NSAID Resistance

Kishore Guda^{1,5}, Stephen P. Fink², Ginger L. Milne⁷, Neil Molyneaux³, Lakshmeswari Ravi², Susan M. Lewis³, Andrew J. Dannenberg⁹, Courtney G. Montgomery¹⁰, Shulin Zhang⁴, Joseph Willis^{4,5,6}, Georgia L. Wiesner⁸, and Sanford D. Markowitz^{2,5,6}

Abstract

HPGD and *SLCO2A1* genes encode components of the prostaglandin catabolic pathway, with *HPGD* encoding the degradative enzyme 15-hydroxyprostaglandin dehydrogenase (15-PGDH), and *SLCO2A1* encoding the prostaglandin transporter PGT that brings substrate to 15-PGDH. *HPGD*-null mice show increased prostaglandin E₂ (PGE₂), marked susceptibility to developing colon tumors, and resistance to colon tumor prevention by nonsteroidal anti-inflammatory drugs (NSAID). But in humans, *HPGD* and *SLCO2A1* mutations have only been associated with familial digital clubbing. We, here, characterize a family with digital clubbing and early-onset colon neoplasia. Whole-exome sequencing identified a heterozygous nonsense mutation (G104X) in the *SLCO2A1* gene segregating in 3 males with digital clubbing. Two of these males further demonstrated notably early-onset colon neoplasia, 1 with an early-onset colon cancer and another with an early-onset sessile serrated colon adenoma. Two females also carried the mutation, and both these women developed sessile serrated colon adenomas without any digital clubbing. Males with clubbing also showed marked elevations in the levels of urinary prostaglandin E₂ metabolite, PGE-M, whereas, female mutation carriers were in the normal range. Furthermore, in the male proband, urinary PGE-M remained markedly elevated during NSAID treatment with either celecoxib or sulindac. Thus, in this human kindred, a null *SLCO2A1* allele mimics the phenotype of the related *HPGD*-null mouse, with increased prostaglandin levels that cannot be normalized by NSAID therapy, plus with increased colon neoplasia. The development of early-onset colon neoplasia in male and female human *SLCO2A1* mutation carriers suggests that disordered prostaglandin catabolism can mediate inherited susceptibility to colon neoplasia in man. *Cancer Prev Res*; 7(8); 805–12. ©2014 AACR.

Introduction

Digital clubbing is characterized by focal bulbous enlargement of the terminal segments of fingers and/or

toes, and in sporadic form is associated with a variety of clinical conditions, including cancer, cardiovascular disease, and inflammatory disorders (1). Familial digital clubbing is a rare inherited genetic disorder that shows an autosomal recessive or a dominant inheritance pattern with variable penetrance, and may occur as part of the syndrome of primary hypertrophic osteoarthropathy (PHO) characterized by periostosis, pachydermia, and digital clubbing (1). In the familial form, a significant gender bias has been noted in which affected males predominate (7:1 male:female ratio; refs. 2, 3). Inherited genetic defects in components of the prostaglandin degradation pathway have been associated with familial PHO/digital clubbing in diverse patient populations from around the world (1–14). These include homozygous loss-of-function mutations in the *HPGD* gene encoding the prostaglandin-degrading enzyme 15-hydroxyprostaglandin dehydrogenase (15-PGDH; refs. 4–8, 13), and both heterozygous and homozygous inactivating mutations in the solute carrier organic anion transporter family, member 2A1 (*SLCO2A1*) gene that encodes the principal prostaglandin transporter (PGT) that mediates prostaglandin uptake into the cell and

Authors' Affiliations: ¹Division of General Medical Sciences-Oncology, ²Division of Hematology and Oncology, Departments of ³Genetics and Genome Sciences and ⁴Pathology, ⁵Case Comprehensive Cancer Center, Case Western Reserve University School of Medicine; ⁶University Hospitals Case Medical Center, Cleveland, Ohio; ⁷Division of Clinical Pharmacology, ⁸Vanderbilt-Ingram Cancer Center, Vanderbilt University School of Medicine, Nashville, Tennessee; ⁹Department of Medicine, Weill Cornell Medical College, New York, New York; and ¹⁰Arthritis and Clinical Immunology Research Program, Oklahoma Medical Research Foundation, Oklahoma City, Oklahoma

Note: Supplementary data for this article are available at Cancer Prevention Research Online (<http://cancerprevres.aacrjournals.org>).

K. Guda, S.P. Fink, G.L. Wiesner, and S.D. Markowitz contributed equally to this article.

Corresponding Author: Sanford D. Markowitz, Case Western Reserve University, 2103 Cornell Road, Wolstein Research Building, 3rd Floor, Mailstop 7285, Cleveland, OH 44106. Phone: 216-368-1976; Fax: 216-368-8928; E-mail: sxm10@cwru.edu

doi: 10.1158/1940-6207.CAPR-14-0108

©2014 American Association for Cancer Research.

hence provides substrate for degradation by 15-PGDH (9–12, 14–19).

Numerous studies have demonstrated an important link between elevated levels of prostaglandin E₂ (PGE₂) and the development of colorectal neoplasia (20–23). PGE₂ can stimulate cell proliferation, angiogenesis, and motility while inhibiting apoptosis and immune surveillance (24). Reduced levels of both PGT and 15-PGDH commonly occur in colorectal neoplasia and are believed to contribute to elevated levels of PGE₂ in the microenvironment, thereby contributing to the pathogenesis of colorectal neoplasia (15, 17, 22, 25–28). Furthermore, there is considerable evidence that inhibitors of PGE₂ production protect against colorectal neoplasia in humans (20, 29–32). This biology has also been demonstrated in murine models, with *HPGD*-knockout mice showing increased colon PGE₂ levels concomitant with being rendered strongly susceptible to induction of colon neoplasms (26, 27). Moreover, the *HPGD*-knockout mouse phenotypes of increased colon tumors and increased colon PGE₂ levels are resistant to correction when this mouse is treated with nonsteroidal anti-inflammatory drugs (NSAID), prototypic inhibitors of PGE₂ production (27). In humans though, colon neoplasia has not been previously characterized in kindred with germline lesions in *HPGD* or in *SLCO2A1*. Here, we identify a multi-generational French-Canadian family presenting with male-restricted digital clubbing accompanied by colon neoplasia. Using whole-exome sequencing, we identify an inactivating mutation in the *SLCO2A1* gene as the underlying pathogenic cause of digital clubbing in this family, and further demonstrate the mutation's association with colon neoplasia and with metabolic resistance to NSAIDs.

Materials and Methods

Patient samples, DNA extraction, and medical record and pathology review

The proband and family members were enrolled into the Institutional Review Board (IRB)-approved Case Western Reserve University (CWRU) Colon Neoplasia Sibling Study (33). A written consent was obtained from the family members for blood collection to extract, store, and analyze the genetic material. Also, wherever applicable, a written consent was obtained from family members for collection of medical records, including photographs, smoking history, cancer diagnoses, surgery and histopathology records, X-ray and any previous clinical genetic testing.

Review of the proband's (1867-01) medical records confirmed the development of adenocarcinoma of the sigmoid colon cancer at the age of 48. Subsequent follow-up colonoscopy examinations did not reveal colonic polyps. Clinical genetic testing of the proband included microsatellite instability analysis of the tumor, and germline sequence analysis of the *MSH2*, *MLH1*, *MSH6*, *PMS2*, and *APC* genes, all of which were normal. Medical and pathology record review of the proband's family members who underwent colonoscopy screening showed multiple members with findings of no polyps at ages 60 and 79 for proband's father,

1867-21; two sessile serrated adenomatous polyps at age 54 for proband's sister, 1867-02; one sessile serrated adenomatous polyp at age 57 for proband's sister, 1867-03; and a sessile serrated adenomatous polyp at age 24 for proband's nephew, 1867-23.

DNA was extracted from whole blood using the Gentra Puregene Blood Kit according to the manufacturer's instructions (Qiagen) for family members. A second sample of blood was collected and sent to the Clinical Laboratory Improvement Amendments (CLIA)-approved clinical molecular laboratory University Hospitals Case Medical Center for retesting and verification of the G104X mutation in *SLCO2A1* gene using Sanger sequencing methods as described below.

Whole-exome capture and deep sequencing

Target capture, library preparation, and deep sequencing were performed by the Oklahoma Medical Research Foundation Next Generation DNA Sequencing Core Facility (Oklahoma City, OK). Target sequence enrichments were performed using the Illumina TruSeq Exome Enrichment Kit as per the manufacturer's protocols (Illumina Inc). Briefly, sample DNAs were quantified using a picogreen fluorometric assay and 3 µg of genomic DNA were randomly sheared to an average size of 300 bp using a Covaris S2 sonicator (Covaris Inc). Sonicated DNA was then end-repaired, A-tailed, and ligated with indexed paired-end Illumina adapters. Target capture was performed on DNA pooled from six indexed samples, following which the captured library was PCR amplified for 10 cycles to enrich for target genomic regions. The captured libraries were precisely quantified using a qPCR-based Kapa Biosystems Library Quantification Kit (Kapa Biosystems) on a Roche Lightcycler 480 (Roche Applied Science). Deep sequencing of the capture enriched pools was performed on an Illumina HiSeq 2000 instrument with 100 bp, paired-end reads to an average read-depth of 70× per sample.

Read mapping, variant detection, and annotation

Burrows-Wheeler Aligner (BWA; ref. 34) or Short Oligonucleotide Analysis Package (SOAP) algorithms (35) were used to align individual 100-bp reads from the raw FASTQ files to the human reference genome (build hg19). Following the conversion of aligned reads in to binary Sequence Alignment/Map (BAM) format, coverage metrics of target bases were calculated using the Picard algorithm (<http://samtools.sourceforge.net>). On average, Picard metrics showed >80% of the target bases covered at 20× read-depth for the samples, with approximately 6% of target bases showing no coverage. Next, sequence variations (both single nucleotide and insertion/deletion) in the germline of respective samples were detected using three variant calling algorithms including, SOAPsnp (35), Genome Analysis Toolkit (GATK; ref. 36), and mPILEUP (37). Genomic variants were mapped to the human transcriptome reference database (RefSeq, build hg19) using a variant annotation tool developed in house (SLATE) that identifies variants mapping to gene coding regions and splice-sites,

including their corresponding positions and codon changes within respective transcripts.

Filtering of variants and identification of gene candidates

Given a dominant inheritance pattern for the disease in this family, we initially identified all variants, including nonsynonymous single-nucleotide variants (SNV), insertion/deletion variants (indel), and splice-site variants in gene coding regions that were cosegregating in individuals 1867-01, -02, -21, and -23. This resulted in a total of 7,292 coding sequence variants. Next, we eliminated variants with a minor allele frequency (MAF) greater than 1% based on the 1000 genome database as well as by clashing against our in-house germline variant database generated from platform-matched whole-exome sequencing of germline samples with European ancestry ($n > 150$). The use of platform-matched in-house database additionally aided in eliminating recurrent artifacts or false positives seen in the Next Generation Sequencing (NGS) data. This resulted in a total of 65 rare candidate coding sequence germline variants passing the above filter criteria. Of the 65 variants, eight were seen in individual 1867-22 who is the mother of the proband, and were subsequently eliminated, resulting in 57 variants. Finally, aligned reads mapping to each of the 57 variant genomic loci were manually reviewed using the Integrative Genomics Viewer (Broad Institute) to eliminate obvious sequence artifacts. In the end, 54 variants mapping to the coding regions of 52 candidate genes passed all the

filtering criteria. Prostaglandin pathway network analysis was performed on the candidate genes by manual curation as well as by using the Ingenuity Pathway Analysis software package (Ingenuity Systems Inc).

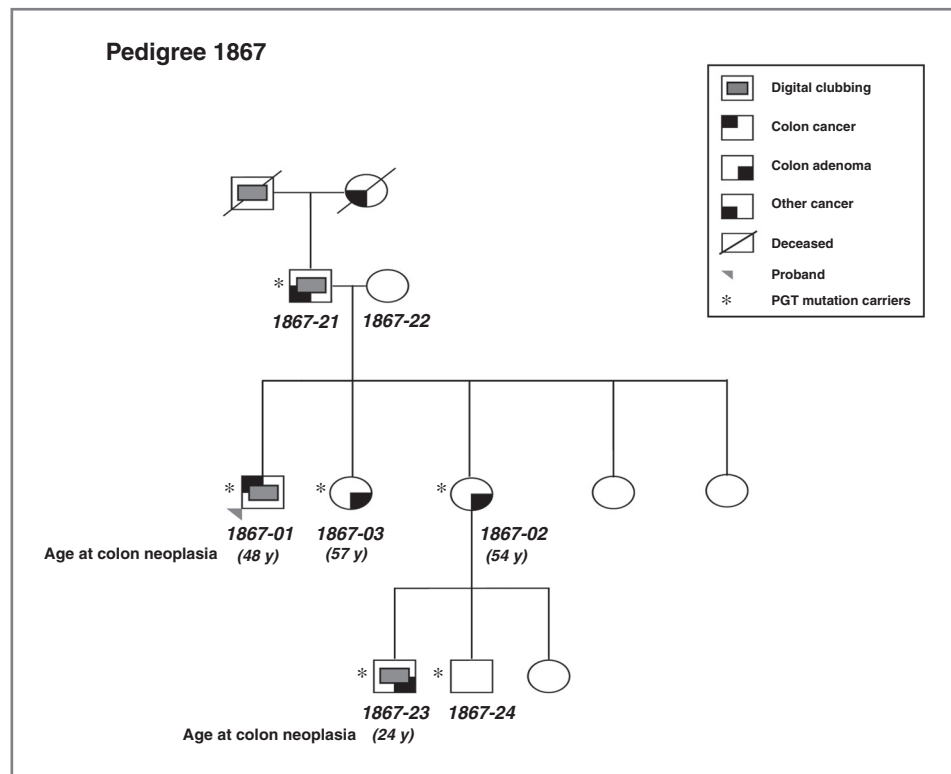
Sanger sequencing

The primers for amplifying the *SLCO2A1* mutant locus in germline DNA, and primers for amplifying coding regions of *SLCO2A1* from formalin-fixed paraffin-embedded DNA are listed in Supplementary Tables S1 and S2. The PCR conditions included 95°C for 4 minutes, 38 cycles of 95°C for 45 seconds, 62.3°C for 30 seconds, and 72°C for 45 seconds. Each reaction was carried out in a 50-μL reaction volume using 2.5 Units of Fast-Taq DNA polymerase (Roche Applied Science) with 25 to 50 ng of template DNA. The PCR products were purified and sequenced using universal M13 forward and reverse primers by Beckman Coulter Genomics. Analysis of Sanger sequencing data was performed using Mutation Surveyor software package (SoftGenetics).

Quantification of urinary PGE-M

The major urinary metabolite of PGE₂, 11α-hydroxy-9,15-dioxo-2,3,4,5-tetranor-prostane-1,20-dioic acid (PGE-M), was analyzed using liquid chromatography/mass spectrometry (LC/MS) with slight modifications to the method previously described by Murphey and colleagues (38, 39). Briefly, 1 mL of urine was converted to the O-methoxime derivative and purified by C18 solid phase extraction before

Figure 1. 1867 family pedigree. Open squares, males; circles, females. Whole-exome sequencing was performed on individuals 1867-21, -22, -01, -02, -03, and -23. *, individuals carrying the *SLCO2A1* G104X heterozygous nonsense mutation. G104X mutation in individual 1867-24 was identified through direct Sanger sequencing.



Downloaded from <http://aacrjournals.org/cancerpreventionresearch/article-pdf/7/8/805/2253414805.pdf> by guest on 15 July 2024

analysis by LC/MS. LC was performed on a 2.0×50 mm, $1.7 \mu\text{m}$ particle ACQUITY BEH C18 Column (Waters Corporation). Mobile phase A was 95:4.9:0.1 (v/v/v) 5 mmol/L ammonium acetate:acetonitrile:acetic acid, and mobile phase B was 10.0:89.9:0.1 (v/v/v) 5 mmol/L ammonium acetate:acetonitrile:acetic acid. Samples were separated by a gradient of 85% to 76% of mobile phase A over 6 minutes at a flow rate of $200 \mu\text{L}/\text{min}$ before delivery to a Thermo Finnigan TSQ Quantum Vantage Triple Quadrupole Mass Spectrometer. Urinary creatinine levels were measured using a test kit from Enzo Life Sciences. The urinary PGE-M level in each sample was normalized using the urinary creatinine level of the sample and expressed in ng/mg of creatinine. Levels of urinary PGE-M in normal, healthy men are 10.4 ± 1.5 ng/mg Cr, whereas levels in normal, healthy women are slightly lower, averaging 6.0 ± 0.7 ng/mg Cr (38, 39).

Results

Family 1867 demonstrates autosomal male digital clubbing and early-onset colon neoplasia

We identified a multi-generational French-Canadian family (family 1867) presenting with digital clubbing restricted to males and showing an autosomal dominant inheritance pattern (Fig. 1). Figure 2 shows representative images of the clubbing phenotype in the male proband (1867-01) demonstrating bilateral bulbous enlargement of terminal segments of fingers and toes. The proband's father is also affected by digital clubbing, as by history was the proband's paternal grandfather (Fig. 1). Moreover, a nephew of the proband (1867-23) has also developed digital

clubbing (Fig. 1). In addition, colon neoplasia was common in the family. In males, colon neoplasia showed early onset, with the proband developing a stage III colon cancer at the age of 48, and, with nephew of the proband, 1867-23, developing a 0.5-cm sessile serrated adenoma at the young age of 24 (Fig. 1 and Table 1). However, colon neoplasia also developed in female family members. One of the proband's sisters, 1867-02, had two sessile serrated adenomatous polyps at the age of 54, the largest being 1 cm in size. A second sister, 1867-03, had a 0.6-cm sessile serrated adenoma at the age of 57. Review of the family's clinical records and molecular genetic testing revealed no evidence of familial adenomatous polyposis (FAP) or hereditary nonpolyposis colorectal cancer (HNPCC).

Identification of inactivating mutation in the *SLCO2A1* gene in family 1867

To identify the genetic basis of digital clubbing in this family, we performed whole-exome sequencing of germline DNA available from 6 individuals, including 3 males affected with clubbing (1867-01, -21, and -23), 2 females unaffected by clubbing (1867-02 and -03), and the mother of the proband (1867-22; Fig. 1). Target capture, deep sequencing, variant calling, and identification of candidate genes were performed as described Materials and Methods. Analysis of the whole-exome data identified 54 rare germline variants that showed segregation in all 3 males affected with clubbing, and that were additionally all present in the 2 unaffected female siblings (Fig. 1). These included one frameshift, 52 missense, and one nonsense mutation that

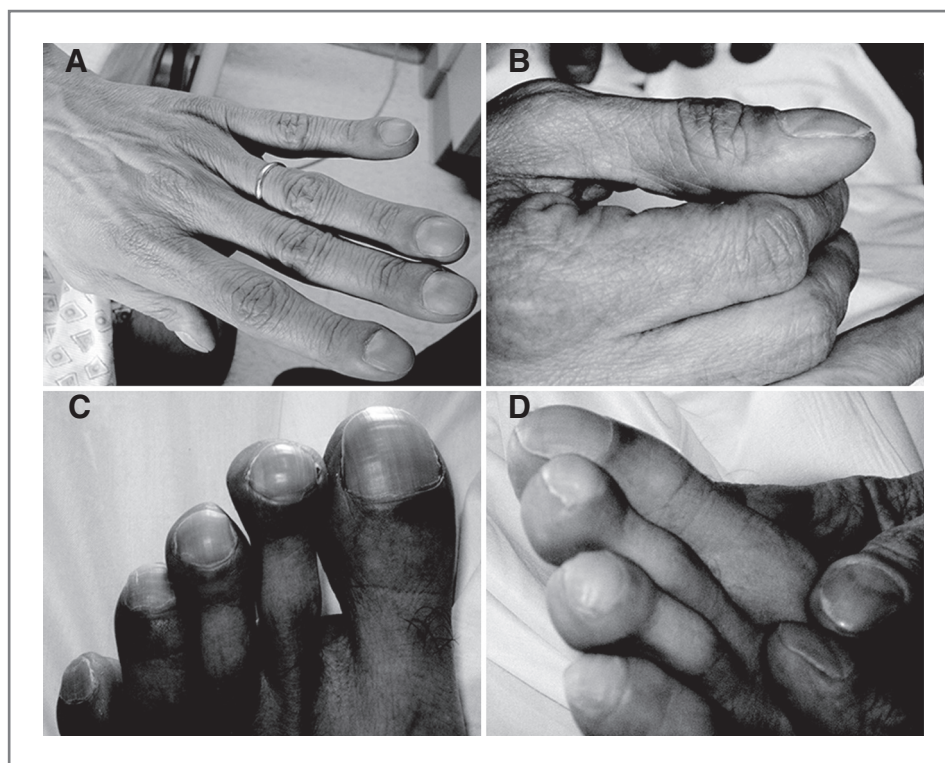


Figure 2. Clinical manifestation of digital clubbing. A–D, representative images from individual 1867-01 (proband) demonstrating bulbous enlargement of fingers (A and B) and toes (C and D).

Table 1. Baseline concentrations of urinary prostaglandin E metabolite (PGE-M) in family members

Individual	Age at follow-up (y)	Gender	Relationship	Digital clubbing	Smoking status (pack-years)	Colon neoplasia (age at diagnosis)	PGE-M (ng/mg Cr)
1867-01	52	Male	Proband	Yes	Never smoker	Sigmoid Colon cancer (48)	56.40
1867-21	88	Male	Father of proband	Yes	Former smoker ^a (93)	None	26.94
1867-23	24	Male	Son of 1867-02	Yes	Never smoker	Sessile serrated adenoma, 0.5 cm (24)	33.96
1867-24	26	Male	Son of 1867-02	No	Former smoker (4)	Unknown	Unknown
1867-02	56	Female	Sister of proband	No	Never smoker	Two sessile serrated adenomas, 1 cm and 0.4 cm (54)	3.09
1867-03	60	Female	Sister of proband	No	Never smoker	Sessile serrated adenoma, 0.6 cm (57)	5.94
1867-22	87	Female	Mother of proband	No	Never smoker	Unknown	13.31

^aSmoked from age 20 to 51 years.

mapped to the coding regions of 52 genes. Given prior studies, we first focused on variants mapping to genes involved in prostanoid synthesis or degradation pathways (1–14). The only such mutant gene was *SLCO2A1* that encodes the PGT and is involved in the uptake of PGE₂ for degradation (40, 41) in which a nonsense mutation (p.G104X, codon 104) was segregating in family 1867 (Figs. 1 and 3). This germline mutation has previously been reported in a single Japanese patient presenting with digital clubbing and periostosis (although with no family history of the disease; ref. 11), and also in a consanguineous Italian family thought to have an autosomal recessive syndrome of digital clubbing, pachydermia, and periostosis (2, 6). These findings strongly suggest that this *SLCO2A1*-inactivating mutation is the underlying cause of digital clubbing in male members of family 1867. Notably, in family 1867 all male individuals with clubbing carried one wild-type *SLCO2A1* allele, indicating the mutant allele as being dominant. Moreover, mutant alleles were also carried in 2

female family members without clubbing as well as in one younger male individual who also lacks clubbing. Thus, the clubbing phenotype seems to be incompletely penetrant, with females in particular resistant to clubbing development.

Increased urinary PGE-M in male individuals with clubbing

Measurements of urinary PGE-M, a stable 15-PGDH pathway end metabolite of PGE₂, are used as an index of systemic PGE₂ levels (25, 38, 39, 42–45). After establishing the mutational status of PGT, we quantified the levels of urinary PGE-M in members of family 1867. As shown in Table 1, affected male members with clubbing and the *SLCO2A1* mutation showed greater than 2.5-fold higher levels of urinary PGE-M when compared with levels (10.4 ± 1.5 ng/mg Cr; ref. 38) reported by our laboratory in normal healthy males. Thus, in males with clubbing, this mutation in the prostaglandin degradation pathway was associated with increased systemic levels of PGE₂. This alteration in PGE metabolism seems to be gender specific and strongly correlates with the clinical restriction of clubbing to only male mutation carriers. Although smoking can be an exogenous cause of increased urinary PGE-M (42, 44), both the proband (1867-01), and his nephew (1867-23), have never smoked, and these two individuals showed the two highest levels of urinary PGE-M.

Elevated PGE-M is resistant to NSAID treatment

Cyclooxygenases (COX)-1 and -2 play critical roles in the synthesis of PGE₂ (46). NSAIDs inhibit COX enzymes and thereby suppress PGE₂ biosynthesis. Both dual inhibitors of COX-1 and COX-2 and selective COX-2 inhibitors have been reported to suppress urinary PGE-M levels in humans (38, 39). Accordingly, we tested the potential of COX inhibitors to reverse the increased urinary PGE-M levels in the proband (1867-01). We first tested sulindac, a prodrug that is metabolized to sulindac sulfide, a dual inhibitor of COX-1 and COX-2. Treatment with oral sulindac at 150 mg

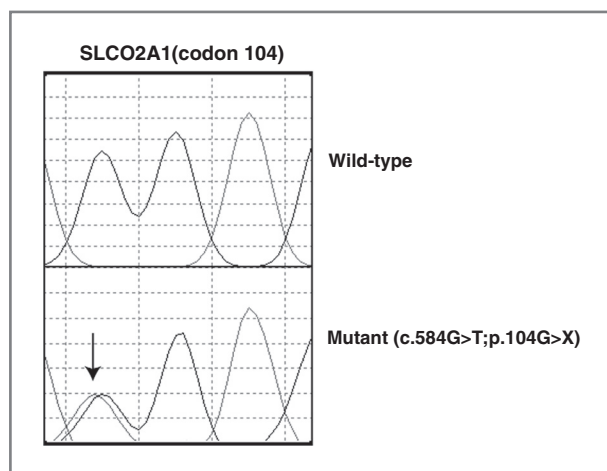


Figure 3. Representative chromatograms from direct Sanger sequencing of *SLCO2A1* codon 104 position in germline DNA showing wild-type (GGA) sequence, and heterozygous mutant (TGA) position (arrow).

twice daily for 4 weeks was associated with about a 40% decline in urinary PGE-M levels, from 56.40 to 33.72 ng/mg Cr, a level that still remained well above the normal range. We then tested celecoxib, a selective inhibitor of COX-2. Treatment with celecoxib 200 mg twice daily for 6 weeks was associated with a 56% decline in urinary PGE-M levels, from 56.40 to 24.79 ng/mg Cr, which again was still elevated well above normal. Thus, although treatment with these two NSAIDs, that both have known colon tumor preventive properties (31, 47), lowered levels of urinary PGE-M, neither drug could effectively normalize the increase in urinary PGE-M caused by the *SLCO2A1* mutation.

Colon neoplasia is coincident with *SLCO2A1* mutation in family 1867

As mentioned above, 4 members of family 1867 had evidence of colon neoplasia. First, the male proband (1867-01) was diagnosed with stage III colon cancer at the age of 48. Second, the proband's nephew (1867-23) who carries the *SLCO2A1* mutation and has clubbing developed a 0.5-cm sessile serrated adenoma at 24 years of age. In Addition, the proband has two female siblings (1867-02 and 1867-03) who both carry the *SLCO2A1* mutation and who also both developed sessile serrated adenomas, although neither demonstrated clubbing (Table 1). The father of the proband (1867-21) underwent colonoscopy at ages 60 and 79, with no evidence of colon neoplasia. The remaining male mutation carrier, 1867-24, age 26, who does not have clubbing, has not been evaluated for colon neoplasia. Overall, 4 first-degree relatives carrying a *SLCO2A1* mutation were affected with colon neoplasia, 1 with early-onset colon cancer, and 3 with sessile serrated adenomas. We found no evidence for biallelic inactivation of the *SLCO2A1* gene in the tumor tissue available from the proband (data not shown). Although our findings suggest that a *SLCO2A1* gene mutation leads to increased systemic levels of PGE₂ and associated clubbing only in males, the pattern of colon neoplasia, nonetheless, suggests that a mutation in *SLCO2A1* may increase the risk of colon neoplasia in both males and females.

Discussion

Here, we identify an autosomal dominant inactivating mutation in the *SLCO2A1* gene (p.G104X) as an underlying cause for male-restricted familial digital clubbing in a French-Canadian family. The finding of male-restricted clubbing in family 1867 is in agreement with prior studies that noted a male predominance of affected individuals

with familial PHO/digital clubbing (2, 4, 6, 10, 12). Although the underlying mechanisms for gender-restricted penetrance are uncertain, it is known that baseline levels of urinary PGE-M, which reflect systemic PGE₂ levels, are higher in healthy males than females (38). Our findings that a PGT mutation leads to higher levels of urinary PGE-M (and presumptively systemic PGE₂) in male mutation carriers than in female mutation carriers suggest one mechanism that could account for gender-specific differences in the incidence of clubbing. Moreover, the dominant phenotype demonstrated by the G104X nonsense mutation suggests that haploinsufficiency of the prostaglandin transporter is sufficient to reduce prostaglandin uptake enough to increase systemic levels of PGE₂ at least in males. Alternatively, the N-terminal fragment encoded by this mutation may have dominant negative function.

The fact that neither treatment with sulindac nor celecoxib led to a normalization of urinary PGE-M levels in the proband is also of interest. As shown in Table 2, although NSAID treatment did lower the proband's levels of urinary PGE-M as compared with baseline, the PGE-M levels still remained significantly above the upper limits seen in normal males. Notably, PGE₂ can induce COX-2 and mPGES-1 in some cell types (48)—a positive feedback loop. We posit that the PGT mutation, by decreasing PGE₂ uptake into the 15-PGDH catabolic pathway, leads to elevated extracellular levels of PGE₂ that results, in turn, in upregulation of enzymes involved in PGE₂ synthesis. Higher doses of NSAIDs may be required to inhibit PGE₂ production in this context. These findings are also consistent with our previous observations in *HPGD*-knockout mice, in which treatment with celecoxib also failed to normalize levels of colonic PGE₂ (26, 27). The finding of limited efficacy of NSAIDs in humans and animals with genetic defects in the PGT-15-PGDH pathway provides strong evidence for the critical role of prostaglandin degradation in regulating PGE₂ levels *in vivo*.

Perhaps the most striking feature of family 1867 is the finding of colon neoplasia in multiple members of the family who carry the *SLCO2A1* mutation, including advanced colon cancer at the age of 48 in the proband (1867-01), sessile serrated adenomas in 2 of his sisters, and a sessile serrated adenoma in 1867-23 (nephew of the proband) at the young age of 24 years (Table 1). Sessile serrated adenomas seem to form via a unique molecular pathway (49). Our findings, if confirmed in additional studies, suggest that prostaglandins may play a role in the pathogenesis of sessile serrated adenomas. In support of this possibility, use of aspirin, a

Table 2. Urinary concentrations of PGE-M in proband 1867-01 following sequential treatment with sulindac and celecoxib, respectively

Treatment	Duration of treatment	PGE-M (ng/mg Cr)
None (baseline from Table 1)	Not applicable	56.40
Sulindac (150 mg, twice daily)	4 weeks	33.72
Celecoxib (200 mg, twice daily)	6 weeks	24.79

known inhibitor of prostaglandin production, has been associated with a reduced risk of serrated polyps (50). It is intriguing that 2 female carriers of the *SLCO2A1* mutation had a history of sessile serrated adenomas in the absence of elevated levels of urinary PGE-M. Perhaps in females, defects in the PGT-15-PGDH pathway increase PGE₂ locally in the colon mucosa, but less so systemically, thereby increasing the local risk of colon neoplasia in the absence of altered systemic levels of PGE₂. We of course cannot exclude the possibility that the development of sessile serrated adenomas in females without clubbing is a phenocopy that is unrelated to any disorder in prostaglandin metabolism. In prior studies, we have shown that *HPGD*-knockout mice, which are defective in prostaglandin degradation, demonstrate both elevated colonic PGE₂ and a marked increase in susceptibility to colon neoplasia (26, 27). In addition, we have demonstrated the continued development of colonic adenomas during celecoxib treatment in *HPGD*-knockout mice and in humans who have below-average levels of 15-PGDH in colonic mucosa (27). We now demonstrate a striking concordance in the phenotypes that result from *HPGD* knockout in the mouse and from *SLCO2A1* mutation in human kindred, which in both instances are associated with increased colon neoplasia and with resistance to NSAIDs. As PGT can transport molecules in addition to PGE₂, it remains possible that the *SLCO2A1* mutation increases the risk of colon neoplasia via a prostaglandin-independent mechanism. Regardless of the underlying mechanism (s) that increases the risk of colorectal neoplasia, our observations support offering colon neoplasia screening at a young age to all individuals who carry inactivating mutations in either *HPGD* or *SLCO2A1*.

References

- Sarkar M, Mahesh DM, Madabhavi I. Digital clubbing. *Lung India* 2012;29:354–62.
- Castori M, Sinibaldi L, Mingarelli R, Lachman RS, Rimo DL, Dallapiccola B. Pachydermoperiostosis: an update. *Clin Genet* 2005;68:477–86.
- Gomez Rodríguez N, Ibanez Ruan J, Gonzalez Perez M. Primary hypertrophic osteoarthropathy (pachydermoperiostosis). Report of two familial cases and literature review. *Reumatol Clin* 2009;5:259–63.
- Uppal S, Diggle CP, Carr IM, Fishwick CW, Ahmed M, Ibrahim GH, et al. Mutations in 15-hydroxyprostaglandin dehydrogenase cause primary hypertrophic osteoarthropathy. *Nat Genet* 2008;40:789–93.
- Yuksel-Konuk B, Sirmaci A, Ayten GE, Ozdemir M, Aslan I, Yilmaz-Turay U, et al. Homozygous mutations in the 15-hydroxyprostaglandin dehydrogenase gene in patients with primary hypertrophic osteoarthropathy. *Rheumatol Int* 2009;30:39–43.
- Diggle CP, Carr IM, Zitt E, Wusik K, Hopkin RJ, Prada CE, et al. Common and recurrent *HPGD* mutations in Caucasian individuals with primary hypertrophic osteoarthropathy. *Rheumatology* 2010;49:1056–62.
- Sinibaldi L, Harifi G, Bottillo I, Iannicelli M, El Hassani S, Brancati F, et al. A novel homozygous splice site mutation in the *HPGD* gene causes mild primary hypertrophic osteoarthropathy. *Clin Exp Rheumatol* 2010;28:153–7.
- Bergmann C, Wobser M, Morbach H, Falkenbach A, Wittenhagen D, Lassay L, et al. Primary hypertrophic osteoarthropathy with digital clubbing and palmoplantar hyperhidrosis caused by 15-PGDH/*HPGD* loss-of-function mutations. *Exp Dermatol* 2011;20:531–3.

Disclosure of Potential Conflicts of Interest

S. Zhang is a consultant/advisory board member for DDC Clinic-Center for Special Needs Children. No potential conflicts of interest were disclosed by the other authors.

Authors' Contributions

Conception and design: K. Guda, A.J. Dannenberg, G.L. Wiesner, S.D. Markowitz

Development of methodology: K. Guda, S. Zhang, J. Willis, S.D. Markowitz
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): S.P. Fink, G.L. Milne, N. Molyneaux, L. Ravi, S.M. Lewis, S. Zhang, J. Willis, G.L. Wiesner, S.D. Markowitz

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): K. Guda, S.P. Fink, N. Molyneaux, A.J. Dannenberg, C.G. Montgomery, S. Zhang, S.D. Markowitz

Writing, review, and/or revision of the manuscript: K. Guda, S.P. Fink, N. Molyneaux, S.M. Lewis, A.J. Dannenberg, S. Zhang, J. Willis, G.L. Wiesner, S.D. Markowitz

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): N. Molyneaux, L. Ravi, S.M. Lewis, J. Willis, S.D. Markowitz

Study supervision: K. Guda, S.P. Fink, S.D. Markowitz

Acknowledgments

The authors thank the members of family 1867 participating in this study.

Grant Support

This study was supported by NIH grants: RO1 CA130901, RO1 CA127306, Case GI SPORE P50 CA150964 (to S.D. Markowitz), and KO8 CA148980 (to K. Guda); Career Development Program of Case GI SPORE (P50 CA150964) award to K. Guda; and the New York Crohn's Foundation (to A.J. Dannenberg).

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked *advertisement* in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received April 3, 2014; revised May 1, 2014; accepted May 13, 2014; published OnlineFirst May 16, 2014.

- Busch J, Frank V, Bachmann N, Otsuka A, Oji V, Metzke D, et al. Mutations in the prostaglandin transporter *SLCO2A1* cause primary hypertrophic osteoarthropathy with digital clubbing. *J Invest Dermatol* 2012;132:2473–6.
- Diggle CP, Parry DA, Logan CV, Laissue P, Rivera C, Restrepo CM, et al. Prostaglandin transporter mutations cause pachydermoperiostosis with myelofibrosis. *Hum Mutat* 2012;33:1175–81.
- Sasaki T, Niizeki H, Shimizu A, Shiohama A, Hirakiyama A, Okuyama T, et al. Identification of mutations in the prostaglandin transporter gene *SLCO2A1* and its phenotype-genotype correlation in Japanese patients with pachydermoperiostosis. *J Dermatol Sci* 2012;68:36–44.
- Seifert W, Kuhnisch J, Tuysuz B, Specker C, Brouwers A, Horn D. Mutations in the prostaglandin transporter encoding gene *SLCO2A1* cause primary hypertrophic osteoarthropathy and isolated digital clubbing. *Hum Mutat* 2012;33:660–4.
- Erken E, Koroglu C, Yildiz F, Ozer HT, Gulek B, Tolun A. A novel recessive 15-hydroxyprostaglandin dehydrogenase mutation in a family with primary hypertrophic osteoarthropathy. *Mod Rheumatol* 2014 Feb 18. [Epub ahead of print].
- Zhang Z, He JW, Fu WZ, Zhang CQ, Zhang ZL. Mutations in the *SLCO2A1* gene and primary hypertrophic osteoarthropathy: a clinical and biochemical characterization. *J Clin Endocrinol Metab* 2013;98:E923–33.
- Holla VR, Backlund MG, Yang P, Newman RA, DuBois RN. Regulation of prostaglandin transporters in colorectal neoplasia. *Cancer Prev Res* 2008;1:93–9.

16. Kanai N, Lu R, Satriano JA, Bao Y, Wolkoff AW, Schuster VL. Identification and characterization of a prostaglandin transporter. *Science* 1995;268:866–9.
17. Markowitz SD. Colorectal neoplasia goes with the flow: prostaglandin transport and termination. *Cancer Prev Res* 2008;1:77–9.
18. Mutoh M, Watanabe K, Kitamura T, Shoji Y, Takahashi M, Kawamori T, et al. Involvement of prostaglandin E receptor subtype EP(4) in colon carcinogenesis. *Cancer Res* 2002;62:28–32.
19. Nomura T, Lu R, Pucci ML, Schuster VL. The two-step model of prostaglandin signal termination: *in vitro* reconstitution with the prostaglandin transporter and prostaglandin 15 dehydrogenase. *Mol Pharmacol* 2004;65:973–8.
20. Dannenberg AJ, Subbaramaiah K. Targeting cyclooxygenase-2 in human neoplasia: rationale and promise. *Cancer Cell* 2003;4:431–6.
21. Dixon DA, Tolley ND, King PH, Nabors LB, McIntyre TM, Zimmerman GA, et al. Altered expression of the mRNA stability factor HuR promotes cyclooxygenase-2 expression in colon cancer cells. *J Clin Invest* 2001;108:1657–65.
22. Markowitz SD, Bertagnolli MM. Molecular origins of cancer: Molecular basis of colorectal cancer. *N Engl J Med* 2009;361:2449–60.
23. Menter DG, Dubois RN. Prostaglandins in cancer cell adhesion, migration, and invasion. *Int J Cell Biol* 2012;2012:723419.
24. Nakanishi M, Rosenberg DW. Multifaceted roles of PGE2 in inflammation and cancer. *Semin Immunopathol* 2013;35:123–37.
25. Backlund MG, Mann JR, Holla VR, Buchanan FG, Tai HH, Musiek ES, et al. 15-Hydroxyprostaglandin dehydrogenase is down-regulated in colorectal cancer. *J Biol Chem* 2005;280:3217–23.
26. Myung SJ, Rerko RM, Yan M, Platzer P, Guda K, Dotson A, et al. 15-Hydroxyprostaglandin dehydrogenase is an *in vivo* suppressor of colon tumorigenesis. *Proc Natl Acad Sci U S A* 2006;103:12098–102.
27. Yan M, Myung SJ, Fink SP, Lawrence E, Lutterbaugh J, Yang P, et al. 15-Hydroxyprostaglandin dehydrogenase inactivation as a mechanism of resistance to celecoxib chemoprevention of colon tumors. *Proc Natl Acad Sci U S A* 2009;106:9409–13.
28. Yan M, Rerko RM, Platzer P, Dawson D, Willis J, Tong M, et al. 15-Hydroxyprostaglandin dehydrogenase, a COX-2 oncogene antagonist, is a TGF-beta-induced suppressor of human gastrointestinal cancers. *Proc Natl Acad Sci U S A* 2004;101:17468–73.
29. Chan AT, Arber N, Burn J, Chia WK, Elwood P, Hull MA, et al. Aspirin in the chemoprevention of colorectal neoplasia: an overview. *Cancer Prev Res* 2012;5:164–78.
30. Arber N, Spicak J, Racz I, Zavoral M, Breazna A, Gerletti P, et al. Five-year analysis of the prevention of colorectal sporadic adenomatous polyps trial. *Am J Gastroenterol* 2011;106:1135–46.
31. Bertagnolli MM, Eagle CJ, Zauber AG, Redston M, Solomon SD, Kim K, et al. Celecoxib for the prevention of sporadic colorectal adenomas. *N Engl J Med* 2006;355:873–84.
32. Cha YI, DuBois RN. NSAIDs and cancer prevention: targets downstream of COX-2. *Annu Rev Med* 2007;58:239–52.
33. Wiesner GL, Daley D, Lewis S, Ticknor C, Platzer P, Lutterbaugh J, et al. A subset of familial colorectal neoplasia kindreds linked to chromosome 9q22.2–31.2. *Proc Natl Acad Sci U S A* 2003;100:12961–5.
34. Li H, Durbin R. Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics* 2009;25:1754–60.
35. Li R, Li Y, Fang X, Yang H, Wang J, Kristiansen K. SNP detection for massively parallel whole-genome resequencing. *Genome Res* 2009;19:1124–32.
36. McKenna A, Hanna M, Banks E, Sivachenko A, Cibulskis K, Kernytsky A, et al. The Genome Analysis Toolkit: a MapReduce framework for analyzing next-generation DNA sequencing data. *Genome Res* 2010;20:1297–303.
37. Li H, Handsaker B, Wysoker A, Fennell T, Ruan J, Homer N, et al. The Sequence Alignment/Map format and SAMtools. *Bioinformatics* 2009;25:2078–9.
38. Murphey LJ, Williams MK, Sanchez SC, Byrne LM, Csiki I, Oates JA, et al. Quantification of the major urinary metabolite of PGE2 by a liquid chromatographic/mass spectrometric assay: determination of cyclooxygenase-specific PGE2 synthesis in healthy humans and those with lung cancer. *Anal Biochem* 2004;334:266–75.
39. Morris PG, Zhou XK, Milne GL, Goldstein D, Hawks LC, Dang CT, et al. Increased levels of urinary PGE-M, a biomarker of inflammation, occur in association with obesity, aging, and lung metastases in patients with breast cancer. *Cancer Prev Res* 2013;6:428–36.
40. Bao Y, Pucci ML, Chan BS, Lu R, Ito S, Schuster VL. Prostaglandin transporter PGT is expressed in cell types that synthesize and release prostanoids. *Am J Physiol Renal Physiol* 2002;282:F1103–10.
41. Schuster VL. Prostaglandin transport. *Prostaglandins Other Lipid Mediat* 2002;68–69:633–47.
42. Duffield-Lillico AJ, Boyle JO, Zhou XK, Ghosh A, Butala GS, Subbaramaiah K, et al. Levels of prostaglandin E metabolite and leukotriene E (4) are increased in the urine of smokers: evidence that celecoxib shunts arachidonic acid into the 5-lipoxygenase pathway. *Cancer Prev Res* 2009;2:322–9.
43. Ferretti A, Flanagan VP, Roman JM. Quantitative analysis of 11 alpha-hydroxy-9,15-dioxo-2,3,4,5,20-pentanor-19-carboxyprostanic acid, the major urinary metabolite of E prostaglandins in man. *Anal Biochem* 1983;128:351–8.
44. Gross ND, Boyle JO, Morrow JD, Williams MK, Moskowitz CS, Subbaramaiah K, et al. Levels of prostaglandin E metabolite, the major urinary metabolite of prostaglandin E2, are increased in smokers. *Clin Cancer Res* 2005;11:6087–93.
45. Seyberth HW, Sweetman BJ, Frolich JC, Oates JA. Quantifications of the major urinary metabolite of the E prostaglandins by mass spectrometry: evaluation of the method's application to clinical studies. *Prostaglandins* 1976;11:381–97.
46. Wang D, DuBois RN. An inflammatory mediator, prostaglandin E2, in colorectal cancer. *Cancer J* 2013;19:502–10.
47. Chan AT, Ogino S, Fuchs CS. Aspirin and the risk of colorectal cancer in relation to the expression of COX-2. *N Engl J Med* 2007;356:2131–42.
48. Diaz-Munoz MD, Osma-Garcia IC, Fresno M, Iniguez MA. Involvement of PGE2 and the cAMP signalling pathway in the up-regulation of COX-2 and mPGES-1 expression in LPS-activated macrophages. *Biochem J* 2012;443:451–61.
49. Crockett SD, Snover DC, Ahnen DJ, Baron JA. Sessile Serrated Adenomas: An Evidence-Based Guide to Management. *Clin Gastroenterol Hepatol* 2013 Nov 19. [Epub ahead of print].
50. Wallace K, Grau MV, Ahnen D, Snover DC, Robertson DJ, Mahne D, et al. The association of lifestyle and dietary factors with the risk for serrated polyps of the colorectum. *Cancer Epidemiol Biomarkers Prev* 2009;18:2310–7.