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

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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.

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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...
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 PCT 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-generation 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 pathogenetic 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://picard.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, SOAPSnip (35), Genome Analysis Toolkit (GATK; ref. 36), and mPILEUP (37). Genomic variants were mapped to the human transcriptome reference database (ReSeq, 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\(^\circ\)C for 4 minutes, 38 cycles of 95\(^\circ\)C for 45 seconds, 62.3\(^\circ\)C for 30 seconds, and 72\(^\circ\)C for 45 seconds. Each reaction was carried out in a 50-\(\mu\)L 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 PGE\(_2\), 11\(\alpha\)-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-methyloxime derivative and purified by C18 solid phase extraction before

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**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. *G104X* mutation in individual 1867-24 was identified through direct Sanger sequencing.
analysis by LC/MS. LC was performed on a 2.0 × 50 mm, 1.7 μm particle ACQUITY BEH C18 Column (Waters Corporation). Mobile phase A was 95.4:9.0:0.1 (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 μL/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...
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 \textit{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 \textit{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 \textit{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 \textit{SLCO2A1} mutation showed greater than 2.5-fold higher levels of urinary PGE-M when compared with levels (10.4 \text{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), and his nephew (1867-23), have never smoked, and these two individuals showed the two highest levels of urinary PGE-M.

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

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

* aSmoked from age 20 to 51 years.
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, 3 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,

<table>
<thead>
<tr>
<th>Table 2. Urinary concentrations of PGE-M in proband 1867-01 following sequential treatment with sulindac and celecoxib, respectively</th>
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<tbody>
<tr>
<td><strong>Treatment</strong></td>
</tr>
<tr>
<td>None (baseline from Table 1)</td>
</tr>
<tr>
<td>Sulindac (150 mg, twice daily)</td>
</tr>
<tr>
<td>Celecoxib (200 mg, twice daily)</td>
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</tbody>
</table>
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 PGE-M receptor (e.g., SLCO2A1) may influence the risk of colorectal adenomas independently of PGE-M levels.

We of course cannot exclude the possibility that the development of sessile serrated adenomas in females without clubbing is a pheno-copy 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 PGE$_2$ and a marked increase in susceptibility to colon neoplasia (26, 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

pgt

w h i c hi nb o t hi n s a r ea s o c i a t dw i t hi n cre a s ed levels of PGE$_2$. We of course cannot exclude the possibility that the development of sessile serrated adenomas in females without clubbing is a pheno-copy 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 PGE$_2$ and a marked increase in susceptibility to colon neoplasia (26, 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

PGT Mutation and Colon Neoplasia

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.

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

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