The role of CysLT1R in animal models of colorectal cancer

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The role of CysLT1R in mouse models of colorectal cancer

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Abstract

Cysteinyl leukotrienes (LTC4, LTD4 and LTE4) are potent pro-inflammatory lipids derived from arachidonic acid and mediate their effect through CysLT1R and CysLT2R. There is a strong correlation between long-standing inflammatory bowel disease where these pro-inflammatory mediators are abundant and colorectal cancer. We have shown that LTD4 via its receptor CysLT1 induces expression of proteins associated with colorectal cancer and promotes proliferation, survival and migration in intestinal epithelial cells. In addition, we have demonstrated that that high expression of CysLT1R in colorectal adenocarcinomas predicts poor prognosis in patients.

In the presented papers in this thesis we investigated the role of CysLT1R in different mouse models of colorectal cancer. In the mouse xenograft model of colon cancer, we were able to observe a reduced tumor growth in response to CysLT1R antagonist treatment. The inhibition of the tumor growth was accompanied with changes in proliferation and apoptosis as determined by reduced Ki-67 expression, increased expression of $p21^{WAF/Cip1}$, cleaved caspase 3 and caspase-cleaved keratin 18. An impaired tumor angiogenesis was also demonstrated by detection of increased levels of VEGF and reduced vessel size. We also investigated the role of CysLT1R in 1) FAP/sporadic colorectal cancer by crossing $ApcMin^{/+}$ mice with mice lacking CysLT1R expression and in 2) colitis-associated colorectal cancer by employing the AOM/DSS-model on mice lacking CysLT1R expression. Interestingly, a reduced polyp formation in a gender-specific manner could be observed in both models. CysLT1R knockout female mice, but not male mice exhibited a reduced polyp formation in the small intestine and colon, respectively. Also, a decreased nuclear expression of β-catenin within the epithelial tumor compartment was determined for CysLT1R mutant female mice in both models. However, the mechanism of tumor progression in FAP/sporadic colorectal cancer and in colitis-associated colorectal cancer might differ as indicated by reduced tumor expression of COX-2 and reduced serum levels of PGE2 in the female double mutant ($CysLT_1R^{-/-}$ $Apc^{Min/+}$) mice, whereas AOM/DSS-treated female single mutant ($CysLT_1R^{-/-}$) mice demonstrated increased serum levels of PGE2. In conclusion, the presented mouse models of colorectal cancer further strengthen our previous *in vitro* findings and highlight the prospect of CysLT1R as an alternative therapeutic approach.

Key words Colorectal cancer, inflammation, CysLT1R

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To my family

Table of contents

List of papers

Paper I (Published)

CysLT1R antagonists inhibit tumor growth in a xenograft model of colon cancer. **Sayeh Savari**, Minghui Liu, Yuan Zhang, Wondossen Sime and Anita Sjölander. PLoS One. 2013 Sep 5;8(9):e73466. doi: 10.1371/journal.pone.0073466.

Paper II (Manuscript)

CysLT1R expression influences intestinal tumorigenesis in a gender-specific manner in the $Apc^{Min/+}$ mouse model. **Sayeh Savari**, Naveen Kumar Chandrashekar, Janina Osman, Kishan Bellamkonda, Desiree Douglas, Gunilla Jönsson, Maria Juhas and Gedas Greicius, Sven Petterson and Anita Sjölander.

Paper III (Manuscript)

The relative expression of the inflammatory receptor CysLT1 determines the tumor incidence in a colitis-associated colorectal cancer model. **Sayeh Savari**, Janina Osman, Naveen Kumar Chandrashekar, Kishan Bellamkonda, Desiree Douglas, Gunilla Jönsson, Maria Juhas and Anita Sjölander.

Abbreviations

5-ASA	5-aminosalicylic acid
AA	arahidonic acid
AC	adenylyl cyclase
AJCC	American Joint Committee on Cancer
AOM	azoxymethane
APC	adenomatous polyposis coli
BrdU	bromodeoxyuridine
CAC	colitis-associated colorectal cancer
CD	Crohn's disease
COPD	chronic obstructive pulmonary disease
COX	cyclooxygenase
$cPLA_2$	cytosolic phospholipase A_2
CRC	colorectal cancer
CREB	cAMP response element-binding protein
CT	computed tomography
CysLT	cysteinyl leukotriene
CysLT1R	cysteinyl leukotriene receptor 1
CysLT2R	cysteinyl leukotriene receptor 2
CysLTR	cysteinyl leukotriene receptor
DAG	1,2-diacylglycerol
DSS	dextran sulfate sodium
Dvl	dishevelled
EGF	epidermal growth factor
EP2	prostaglandin E receptor 2

EP4	prostaglandin E receptor 4
FAP	familial adenomatous polyposis
FBS	fetal bovine serum
FLAP	5-lipoxygenase activating protein
Fz	frizzled
GAPDH	glyceraldehyde-3-phosphate dehydrogenase
GDP	guanine nucleotide diphosphate
GEF	GDP/GTP exchange factor
GPCR	G-protein coupled receptor
GSK-3β	glycogen synthase kinase 3-beta
GTP	guanine nucleotide triphosphate
HNPCC	hereditary nonpolyposis colorectal cancer
HPETE	hydroperoxyeicosatetraenoic acid
IBD	inflammatory bowel disease
IESC	intestinal epithelial stem cell
IL-6	interleukin-6
IP_3	inositol 1,4,5-triphosphate
LEF/TCF	lymphoid enhanced factor/T-cell factor
LOH	loss of heterozygosity
LOX	lipoxygenase
LRP5/6	lipoprotein-related protein 5 or 6
LT	leukotriene
LTA4	leukotriene A4
LTB4	leukotriene B4
LTC4	cysteinyl leukotriene C4
LTD4	cysteinyl leukotriene D4
LTE4	cysteinyl leukotriene E4
Min	murine intestinal neoplasia
MRP1	multidrug resistance-associated protein 1

MSI	microsatellite instability
MUC2	mucin 2
NF-κB	nuclear factor-κB
NSAIDS	non-steroidal anti-inflammatory drugs
$p90^{RSK}$	p90 ribosomal S6 kinase
PGE2	prostaglandin E2
PI3K	phosphatidylinositol 3-kinase
PIP_2	phosphatidylinositol 4,5-biphosphate
PKC	protein kinase C
PLC-β	phospholipase C-β
RNI	reactive nitrogen intermediates
ROS	reactive oxygen species
SRS	slow-reacting substance
STAT3	signal transducer and activator of transcription 3
TCC	transitional cell carcinoma
TNF-α	tumor necrosis factor-alpha
UC	ulcerative colitis
UICC	International Union Against Cancer
VEGF	vascular endothelial growth factor

Introduction

The first recorded descriptions of cancer are from the ancient Egypt (approx. 3000 BC). The word cancer originates from the findings of the Greek physician Hippocrates (460-375 BC), whom probably perceived the outgrowth of tumors similar in appearance to crabs. The Greek term for crab was later translated by the Roman physician Celsus (25 BC-50 AD) to the Latin *cancer* (1). Although tremendous progress has been made in the treatment of cancer, from the breakthrough of surgery during the 19th century and today's use of drugs as adjuvant to surgery and radiation therapy combined with early detection possibilities, cancer still remains the second major cause of lethality worldwide (2). The understanding that various factors such as chemical carcinogens, ionizing radiation and viruses can cause non-inherited cancer by inducing genetic damage, resulted eventually in the pinpointing of genes that were pivotal in cancer development. In the 1970's the scientists classified these genes in two families, referred to as proto-oncogenes and tumor suppressor genes (3). Accumulation of mutations in these genes is believed to cause cellular alterations that convey growth advantage and clonal expansion in analogy of Darwinian evolution, and subsequently cancer development. The essential cellular alterations that are required for neoplastic transformation, referred to as hallmarks of cancer and includes sustained proliferative and replicative ability, evasion of growth suppression and cell death, and induction of angiogenesis and invasion/metastasis (4). More recently, reprogramming of energy metabolism and evasion of immune destruction have emerged as new hallmarks of cancer. The inflammatory milieu has also been appreciated as one of the enabling characteristics of cancer, fostering several of these hallmarks (5). One of the most established connections between inflammation and cancer is between long-standing inflammatory disease (IBD), such as ulcerative colitis (UC) and Crohn's disease (CD) and colorectal cancer (CRC) (6, 7).

We have previously shown that the pro-inflammatory lipid derived cysteinyl leukotriene D4 (LTD4) activation of the cysteinyl leukotriene receptor 1 (CysLT1R) induces proliferation, survival and migration in intestinal epithelial cells (8, 9). Moreover, high CysLT1R expression in colorectal adenocarcinoma tissues of Dukes' B patients has been associated with poor survival prognosis (10).

The forehand interest was to investigate the role of the CysLT1R in colorectal cancer development, taking into account the tumor microenvironment and employing mouse models.

Background

The intestinal tract and its barrier function

The intestinal tract is a tubular construct composed of three tissue layers. The outermost layer with sheets of innervated smooth muscle, the stromal layer in the middle and the innermost epithelial layer. Moreover, the epithelial monolayer of the intestine is the largest mucosal surface in mammalians, covering a surface area of 400 m^2. In addition to water- and nutrition absorption it functions as a barrier, separating the mammalian host from the external environment. The small intestine is subdivided into the duodenum, jejunum and ileum. The absorptive area of the small intestine is profoundly increased by luminal protrusions, villi and invaginations into the submucosa, crypts of Lieberkün. The large intestine on the other hand is composed of a flat epithelium with only crypts and is roughly subdivided in cecum, colon and rectum/anus. Notably, the intestinal epithelium is continually renewed every ~ 5 day by proliferation of intestinal epithelial stem cells (IESCs) at the base of the crypts. This creates an upward movement of proliferative progenitor cells and shedding of differentiated cells at the top of villi/crypts (11, 12) (Figure 1).

There are four types of terminally differentiated cell types. Majority being absorptive enterocytes, which have a brush border termed microvilli at their apical surface that is of assistance in their digestive task. The other three differentiated cells are secretory and part of maintaining the barrier or digestive function. The luminal secretion of antimicrobial proteins and mucins and by Paneth cells and goblet cells, respectively, provides a physical and biochemical barrier. Conversely, the secretion of hormones such as serotonin and secretin by enteroendocrine cells regulates digestion. Paneth cells differ from the other cell types in that they reside in the crypts whilst the rest reside in the luminal part of the small intestine. However, the crypts of the large intestine in mammals lack Paneth cells. The differentiated cells of the large intestine reside in the upper one third of the crypt epithelium, while the proliferating compartment makes up the rest (11, 12).

Mucins are highly glycosylated proteins and they are the first line of defense, not only against microbes but also mechanical- and chemical stress. Mucin 2 (MUC2) is a secreted gel forming mucin and the most prominent in the mucosal layer of the intestine. It is secreted by differentiated goblet cells and is responsible for their characteristic morphology with apparent subapical granules (13). The importance of

MUC2 has been emphasized in Muc2$^{-/-}$ mice, which develop spontaneous colitis and are predisposed to CRC (14-16).

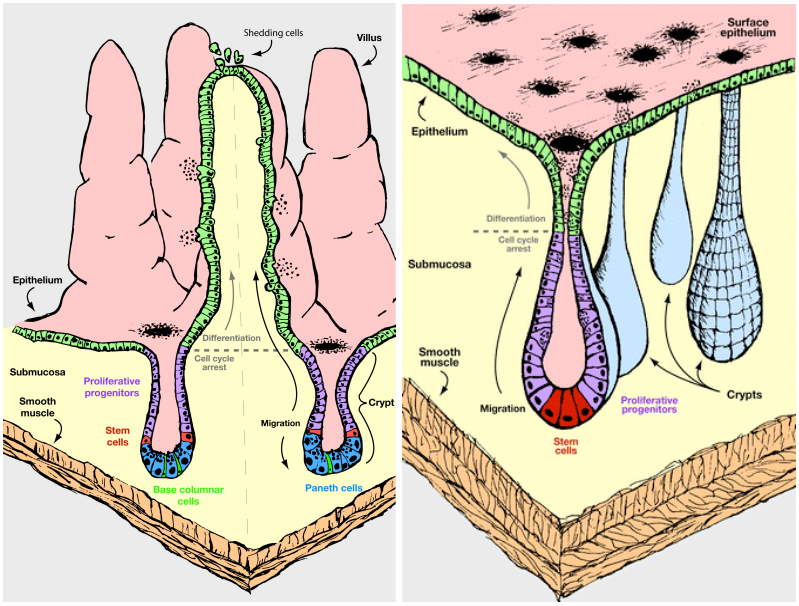

Figure 1. The structure of the small intestine (left) and large intestine (right). Adapted from Clevers, H *et al.*, 2004.

The pathogenesis of the intestine

Inflammatory bowel disease

IBD is a chronic inflammatory condition of the intestine. The two major forms of IBD are UC and CD. UC may affect the mucosal lining of the colon in a continuous pattern, initiating in the rectum and involving part of or the entire colon. Crohn's disease may affect the whole intestinal wall and can occur in patches anywhere along the gastrointestinal tract. Although they are distinct diseases they share clinical symptoms such as diarrhea, abdominal pain, gastrointestinal bleeding and weight loss (17). The pathogenesis of IBD have a genetic basis and genome-wide association studies have identified loci that overlap and others that are unique for either UC or CD (18). The role of lipid inflammatory mediators has been implicated and one of the overlapping genetic risk factors for UC and CD is *PTGER4,* the prostaglandin E

receptor 4 (EP4), which acts as a receptor for the lipid inflammatory mediator prostaglandin E2 (PGE2) (19, 20). However, IBD patients have demonstrated relapse receiving non-steroidal anti-inflammatory drugs (NSAIDS), inhibitors of the cyclooxygenase (COX) enzyme, responsible for production of prostanoids such as PGE2. Accordingly, mice that were either deficient in PTGER4 (*Ptger4*$^{-/-}$) or received NSAIDS exhibited increased susceptibility in the dextran sulfate sodium (DSS)-induced model of colitis (21). An increased susceptibility has also been observed in DSS treated mice deficient in COX-1 (*Ptgs1*$^{-/-}$) and COX-2 (*Ptgs2*$^{-/-}$) (22). Another group of lipid inflammatory mediators that has been implicated in the pathogenesis of IBD are the leukotrienes (LTs). Increased levels of leukotriene B4 (LTB4) and cysteinyl leukotriene E4 (LTE4) have been observed in the colonic mucosa and in the urine of patients with active IBD(23, 24). In addition, animal models of colitis have shown that both pharmacological inhibition and deletion of the gene encoding 5-LOX, the enzyme responsible for production of leukotrienes, reduces the severity of the disease (25-27).

Colitis associated colorectal cancer

There is an established connection between inflammation and cancer (5, 28), and perhaps one of the best characterized is between IBD and colorectal cancer, referred to as colitis-associated colorectal cancer (CAC). Although CAC represents only 1-2% of all cases of colorectal cancer (29) (Figure 2), these patients have a high mortality rate and an approximate 50% 5-year overall survival have been estimated for CAC patients (30). Crohn *et al.* were the first to describe the increased risk of developing colorectal cancer in IBD patients in 1925 (31). Population-based studies have estimated that IBD patients, compared to age-matched healthy individuals have a 2- to 5- fold increased risk of developing colorectal cancer (32). Family history of colorectal cancer, early onset and concomitant primary sclerosing cholangitis are some of the established risk factors of developing colorectal cancer in IBD patients. Other risk factors are duration, extent and severity of inflammation of the affected intestinal mucosa (33). Treatment of IBD patients with the anti-inflammatory agent 5-aminosalicylic acid (5-ASA) has demonstrated a reduced risk of developing CAC (34-36). In line with these studies is the reduction of dysplatic colon lesions in 5-ASA treated mice in the azoxymethane (AOM)-DSS model of CAC (37).

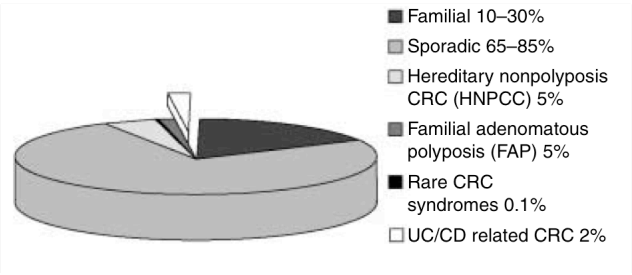

Figure 2. Prevalence and etiology of colorectal cancer (CRC) in the general polpulation. Adapted from P. Munkholm, 2003.

Sporadic and hereditary colorectal cancer

CRC is the third most prevalent cancer, affecting men and women almost equally and the fourth leading cause of all cancer-related deaths worldwide (38). The majority of all CRC cases are either sporadic (65-85%) or hereditary (10-30%) (39)(Figure 2).

Pathogenesis of CRC (CAC vs. sporadic CRC)

The pathogenesis of sporadic/familial CRC shares many similarities with CAC, independently of evident inflammatory disease in the former case. In general, CRC develops from dysplastic precursor lesion and the sequence of progression that follows includes formation of adenoma and subsequently carcinoma (40). Although an alternative sequence have been suggested for CAC development including various degree of dysplasia without the formation of the adenoma (Figure 3). The adenoma, a distinct area of neoplasia can easily be removed by endoscopic polypectomy, whereas the dysplastic lesions in CAC patients can be polypoid/nonpolypoid localized or multifocal, which could require the removal of the entire colon-rectum. These morphological changes are accompanied with a specific sequence of molecular alterations acquired throughout the tumor progression. Many of these alterations are common features for sporadic CRC and CAC, such as development of aneuploidy (chromosomal instability), microsatellite instability (MSI), DNA methylation, activation of the oncogene *KRAS*, increased expression of COX-2, allelic deletion and eventual loss of function of *p53*, adenomatous polyposis coli (*APC*), and *DCC/DPC4* (41) (Figure 3). However, there are some differences between sporadic CRC and CAC in the frequency and timing at which these molecular alterations occur. For example, allelic deletion of APC is one of the earliest events in the pathogenesis of sporadic CRC while occurring later and less frequent in CAC (42-44). It has been estimated that nearly 70% of sporadic tumors harbor allelic *APC* mutations, while approximately 30% of colitis-associated tumors seem to harbor the same mutation

(45, 46). On the other hand, loss of function mutation of p53 is more common and occurs early in the progression of CAC. Approximately 50-80% of colitis-associated tumors have been shown to have allelic deletion of *p53*, and loss of p53 function is an important genetic factor in the malignant progression of CAC (47).

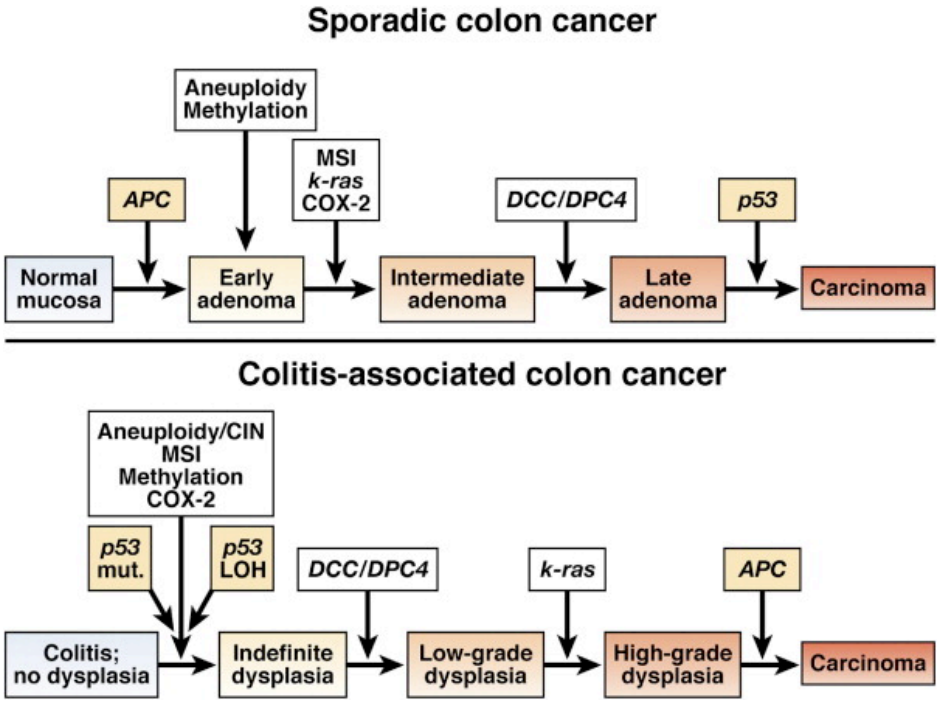

Figure 3. Molecular pathogenesis of sporadic colorectal cancer (top) and colitis-associated colorectal cancer (bottom). Adapted from Itzkowitz *et al.*, 2011.

Even though chronic inflammation might not be required for initial pathogenesis of sporadic CRC, there are evidences that inflammation could be of importance for perpetuation of the disease. Tumors of CRC display increased inflammatory infiltration of immune cells and expression of proinflammatory cytokines. In general, high frequency of tumor infiltrating lymphocytes is associated with good prognosis (48). The subtype of tumor infiltrating lymphocyte has also been shown to have prognostic value. Low $CD4^+$:$CD8^+$ and high $CD3^+$:$Foxp3^+$ ratio of tumor infiltrating lymphocytes are considered conveying a better clinical outcome and higher 5-year survival for colorectal patients (49, 50). In addition to producing mutagens such as reactive oxygen species (ROS) and reactive nitrogen intermediates (RNI) that may

induce DNA damage and facilitate tumor progression (51), the infiltrating immune cells can also secrete inflammatory cytokines. The best-characterized cytokines in promotion of CAC are tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) (52, 53). IL-6 signaling via signal transducer and activator of transcription 3 (STAT3), and TNF-α signaling via nuclear factor-κB (NF-κB) have been implicated in the pathogenesis of CAC (41). Activation of these transcription factors induces expression of genes such as *Bcl2* or *Bcl-xL* that suppresses apoptosis, *Cyclin D1* or *c-Myc* that mediate proliferation, and vascular endothelial growth factor (*VEGF*) that promotes angiogenesis (40).

FAP and the Wnt/β-catenin signaling pathway

Inherited forms of colorectal cancer harbor germline gene mutations and include familial adenomatous polyposis (FAP), hereditary nonpolyposis colorectal cancer (HNPCC), hamartomatous polyposis and other more rare variants. There is a difference between hereditary and familial colorectal cancer, the latter comprises a predisposition but without a defined genetic basis. It is estimated that the lifetime risk of developing familial colorectal cancer increases by approximately 20% with affected first and/or second degree relatives while reaching 80-100% in hereditary cases (54).

The autosomal dominant inherited disorder FAP was first described by Lockhart-Mummery in 1925 (55). FAP is characterized by hundreds to thousands of colorectal small adenomatous polyps that usually emerges in the second-third decade of life and if not dealt with surgically, progresses to colorectal cancer (56). Positional cloning has verified germline mutations of the tumor suppressor *APC* gene responsible for FAP (57-59). The majority of these are mutations that result in truncated APC protein with aberrant function. Colorectal adenomas of FAP patients have shown to harbor an additional (somatic) mutation or display loss of heterozygosity (LOH) of the second *APC* allele (60, 61).

The APC protein regulates the activity of β-catenin via the canonical Wnt signaling pathway. β-catenin has several subcellular localizations, at the cell membrane where it maintains cell-cell adhesions together with E-cadherin, in the cytoplasm where it is tightly regulated by a complex of proteins or in the nucleus where it has a transcriptional activity. The canonical Wnt pathway is involved in physiological processes such as embryonic development but also in various cancers, including colorectal cancer. The cytoplasmic β-catenin is in the absence of Wnt ligands targeted by the destruction complex including APC, glycogen synthase kinase 3-beta (GSK-3β), Axin and other proteins. Subsequently, this leads to the phosphorylation, ubiquitination and finally proteasomal degradation of β-catenin. In contrast, upon Wnt binding to the G-protein coupled receptor Frizzled (Fz), the scaffold protein Dishevelled (Dvl) is recruited, which leads to phosphorylation of the co-receptor lipoprotein-related protein 5 or 6 (LRP5/6) and further recruitment of Axin and GSK-3β. Prevented assembly of the destruction complex allows activation of β-

catenin and its translocation to the nucleus where it together with transcriptional factors such as lymphoid enhanced factor/T-cell factor (LEF/TCF) can drive transcription of oncogenic genes such as *Cyclin D1* or *c-Myc* (62) (Figure 4).

Approximately 90% of sporadic colorectal cancers harbor activating mutations in the Wnt pathway. Other mutations that result in constitutive active Wnt signaling are those occurring in β-catenin, Axin, GSK-3β but these are significantly less frequent (~10%) than APC mutations (~80%) (63). Activation of the Wnt pathway is important for adenoma initiation but insufficient by itself to drive carcinogenesis. Accordingly, it has been demonstrated that activation of additional signaling pathways, such as those mediated by KRAS and nuclear localization of β-catenin are required for CRC progression (64).

There are alternative ways of achieving nuclear accumulation of ß-catenin, without an activating mutation in the Wnt pathway. Interestingly, LTD4 and PGE2 stimulation of CysLT1R and prostaglandin E receptor 2 (EP2), respectively, have been demonstrated to induce β-catenin nuclear accumulation and transcriptional activity in colon cancer cells and stimulate growth (65, 66).

The role of PGE2 in colorectal cancer has been further established using a mouse model of FAP. Crossbreeding with mice lacking expression of COX-2 (*Ptgs2*) and the PGE2 receptor EP2 (*Ptgerep2*) has demonstrated attenuation in intestinal polyp formation (67, 68). Several animal models exist for FAP. The first described was the murine intestinal neoplasia (Min) model, which developed multiple benign adenomas predominantly in the small intestine (69). The gene responsible for this phenotype was later identified as the murine homolog of the *APC* gene (70). Gene targeting strategies has led to additional *Apc* knockout models such as Apc1638N and ApcΔ716 (71, 72).

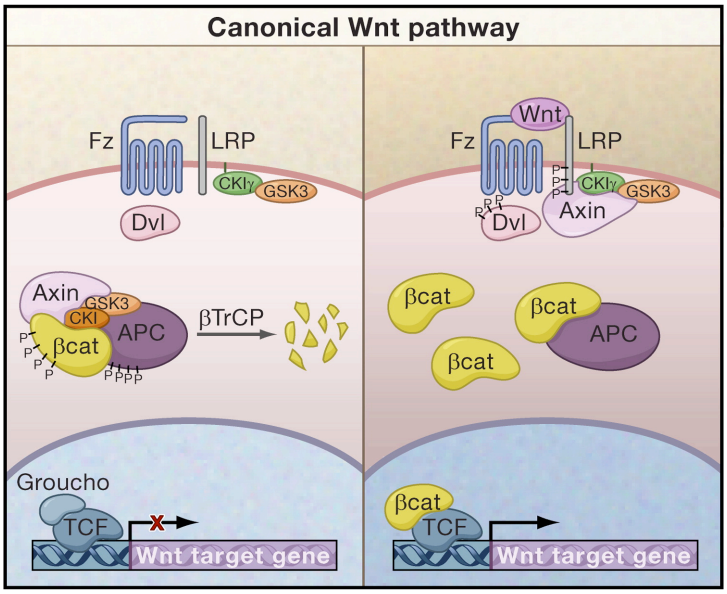

Figure 4. Canonical Wnt/β-catenin signaling pathway. Adapted from H. Clevers, 2006.

Tumor staging and treatment

Colorectal cancer can be diagnosed with colonscopy or sigmoidoscopy and tumor biopsy. Other imaging tests such as computed tomography (CT) colonography could be used to evaluate possibility of distant metastasis (73, 74). Staging of the disease is the strongest predictor of survival and of importance for the determination of treatment strategy. The most common is the TNM (Tumor-Node-Metastasis) staging system of the American Joint Committee on Cancer (AJCC) and the International Union Against Cancer (UICC) (75). The TNM system assigns a stage based on the degree of invasion of the intestinal wall by the primary tumor (T), the degree of lymphatic node involvement (N) and degree of metastasis (M). Surgery is the main curative treatment in localized colorectal cancer. Although in node-positive (stage II-III) disease, preoperative neoadjuvant treatment such as short-course radiotherapy or long-course chemoradiotherapy is recommended (73, 74). In colorectal cancer patients with potentially resectable liver-only or lung-only metastases palliative chemotherapy could be beneficial in terms of survival. Targeted treatment with EGFR monoclonal antibodies such as cetuximab has been one the major advances in the management of metastatic disease in colorectal cancer patients with wild-type *KRAS* (76).

Eicosanoids

Eicosanoids derived from the Greek word *eicosa* meaning 20, describes an important class of lipid mediators derived from 20-carbon polyunsaturated fatty acids. The main eicosanoid precursor in most mammalian systems is arahidonic acid (AA), which belongs to the ω-6 family of essential polyunsaturated fatty acids with 4-*cis* double bonds (20:4ω6) (77). AA resides predominantly at the second carbon position of membrane phospholipids and its release is mainly initiated by cytosolic phospholipase A_2 ($cPLA_2$) in response to mechanical stress or specific extracellular stimuli (78). Cystosolic AA is metabolized via three enzymatic pathways. The generated eicosanoids are prostanoids (prostaglandins and thromboxanes), synthesized via the COX pathway, leukotrienes and hydroxyl eicosatetraenoic acids (HETEs), which are generated via the lipoxygenase (LOX) pathway and epoxides via the cytochrome P-450 epoxygenase pathway (Figure 5).

In the early 1930s the vasodepressor and smooth muscle-stimulating activity of "prostaglandins" was discovered. However, the structure and origin of these compounds were not reported until 30 years later by Bergström and Samuelson, for which they were rewarded with the Nobel prize in 1982 (79). These two scientists contributed also to the elucidation of the 5-LOX pathway and the discovery of cysteinyl leukotrienes as the slow-reacting substance (SRS). These compounds were responsible for the smooth muscle contraction in the perfusate of guinea pig lung treated with cobra venom that was observed in 1938 by Feldberg and Kellaway. They were also later found to be the mediators in asthma and other types of immediate hypersensitivity reactions, referred to as slow-reacting substance of anaphylaxis (SRS-A) (80, 81). In addition to their role in acute systemic inflammatory responses (78), the role of eicosanoids in the maintenance of intestinal homeostasis (82) and their dysregulated functions in pathological conditions such as chronic inflammation and cancer is well established (83, 84).

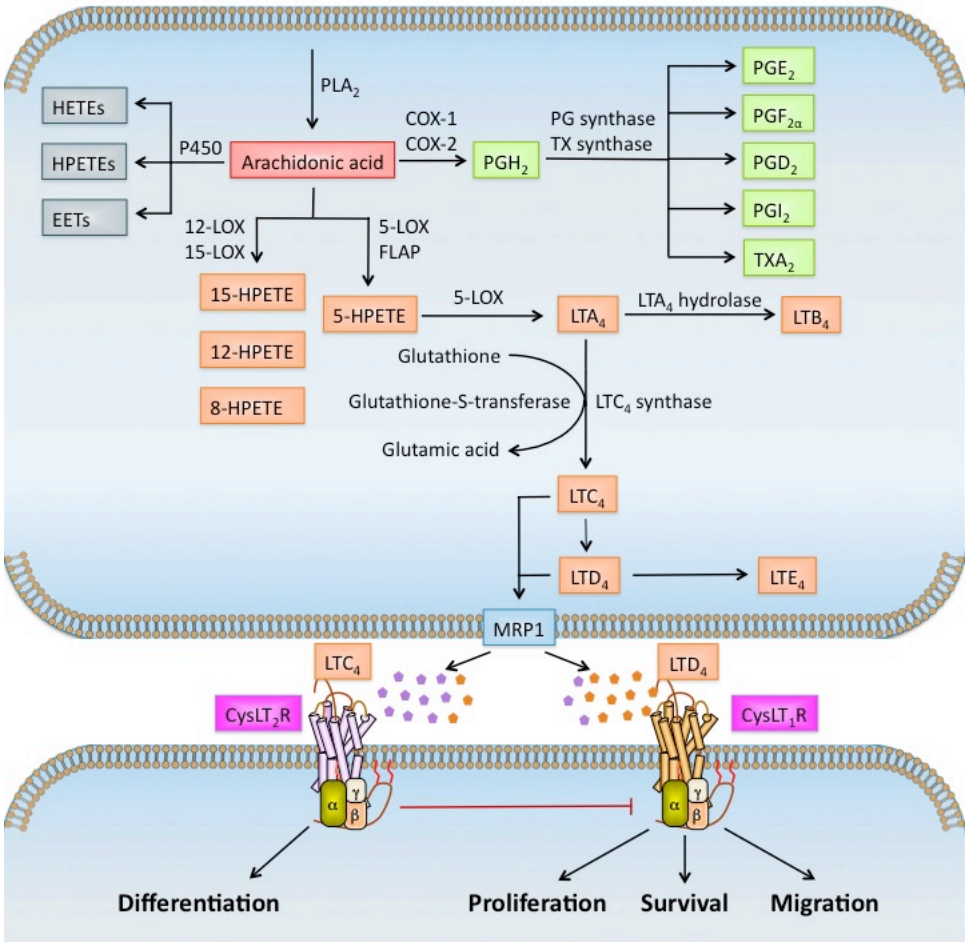

Figure 5. Arachidonic acid metabolism and cysteinyl leukotriene signaling. Adapted from Savari *et al.*, 2014.

The 5-LOX pathway

Leukotrienes

In contrast to prostaglandins, which are produced by most cells, the production of LTs is predominantly constricted to leukocytes such as mast cells, eosinophils, basophils and macrophages. The term *leukotriene* denotes the cell type (*leukocytes*) in which the originally were identified and the presence of three conjugated double bonds (*trienes*) (85).

The mammalian lipoxygenase pathway consists of three enzymes with ability of catalyzing the insertion of an oxygen molecule into AA, at positions 5, 12 or 15 and

generating hydroperoxyeicosatetraenoic acid (i.e. 5-, 12- or 15-HPETE)(77). The 5-lipoxygenase pathway (5-LOX) is involved in the biosynthesis of leukotrienes. The catalytic task of 5-LOX is facilitated 5-lipoxygenase activating protein (FLAP), which does not exert any enzymatic activity. The unstable 5-HPETE undergoes immediate dehydration, yielding leukotriene A4 (LTA4). Depending on the cellular context, three metabolic fates are possible for LTA4: hydrolysis, conjugation with glutathione or transcellular metabolism. Hydrolysis by the cytosolic LTA4 hydrolase generating LTB4, a potent neutrophil chemoattractant and promoter of leukocyte adhesion to vascular endothelium. The integral membrane protein LTC4 synthase conjugates reduced gluthathione to LTA4 to produce cysteinyl leukotriene C4 (LTC4). After carrier-mediated transport to the extracellular *milieu* by transporters such as multidrug resistance-associated protein 1(MRP1), LTC4 undergoes cleaveage of the glutamic acid moiety to form LTD4 by the catalytic action of γ-glutamyl transpeptidase. LTD4 is further metabolized by dipeptidase through cleavage of the glycine moiety to yield cysteinyl leukotriene E4 (LTE4) (Figure 5). The last three mentioned derivatives of LTA_4 are collectively termed *cysteinyl leukotrienes* (CysLTs) due to a common cysteine residue (78, 86, 87). Although 5-LOX is predominately expressed by leukocytes such as neutrophils, eosinophils, macrophages and mast cells, the expression of LTC4 synthase and LTA4 hydrolase are expressed more ubiquitously and CysLTs can be produced by nonleukocytes via uptake of exogenous LTA4, a process referred to as transcellular metabolism (88). As previously stated, CysLTs have been shown to induce airway mucus secretion, increased vascular permeability, eosinophil chemotaxis, and bronchoconstriction (89-92).

Leukotriene receptors

Early pharmacological studies of the smooth muscle contractile properties of different cysteinyl leukotrienes and blocking of contractions with different antagonists indicated the possibility of at least two receptors (93-95). Eventually these CysLT receptors (CysLTRs) received their nomenclature based on their sensitivity to "classical" antagonists including montelukast, zafirlukast, pranlukast and MK571. Accordingly, CysLT1R is sensitive to classical antagonists while the effects of cysteinyl leukotriene receptor 2 (CysLT2R) are not inhibited by these antagonists (96). Cloning and characterization of the human CysLT1 and CysLT2 receptors revealed their position on chromosomes X (Xq13–Xq21) and 13 (13q14), respectively (97, 98). These receptors are seven transmembrane G-protein-coupled receptors (GPCRs) and CysLT-ligand binding induces conformational changes resulting in G-protein activation, including GDP to GTP exchange, GTP hydrolysis and intracellular events such as increase in cytosolic concentration of Ca^{2+} (99).

CysLT1R has high affinity for LTD4, while CysLT1R has a weaker but equal affinity for LTD4 and LTC4 (97, 98). The expression patterns of these receptors are tissue

dependent but not mutually exclusive. Higher expression of the human CysLT1R can be observed in the spleen, peripheral blood leukocytes and less expression in lung, small intestine, pancreas and placenta and little or no expression in the liver, colon, kidney, skeletal muscle, thymus, ovary, testis, heart and brain. In addition to high human CysLT2R expression in the spleen and peripheral blood leukocytes, high expression of CysLT2R has also been observed in the heart, adrenal gland and brain (99). The human CysLT1R shares 38% amino acid identity with the human CysLT2R, and 87% with the mouse CysLT1R (98, 100). Molecular cloning and characterization of the mouse CysLT1R have revealed two potential isoforms resulting from alternative splicing (100, 101). Kanaoka *et al.* have reported the generation of mice with a disrupted coding region of the *CysLT1R* gene that is common for both isoforms (102). A comparison between the human and mouse CysLTRs is described in Table 1. The presence of additional CysLT receptors such as GPR17, P2Y12 and CysLTER has also been proposed (103-105). LTB4 mediates signaling via two GPCRs, BLT1 and BLT2 (106, 107). BLT1 is a LTB4 high affinity receptor highly expressed in peripheral blood leukocytes while BLT2 is a LTB4 low affinity receptor and present in most human tissues, with the highest expression in spleen, liver, ovary, and peripheral blood leukocytes (108, 109). By mediating the effects of LTB4, the receptors BLT1 and BLT2 play an important role in the host immune defense and the pathogenesis of inflammatory diseases (109). In polymorphonuclear leukocytes such as neutrophils, LTB_4 induces chemotactic response (106, 110), adherence to the endothelium (111), production of superoxides (112), release of lysosomal enzymes (113), phagocytosis of bacteria (114) and increased survival (115).

Table 1. Human and mouse cysteinyl leukotriene receptors. Adapted from Singh *et al.*, 2010.

Receptors	Human $CysLT_1$	Human $CysLT_2$	Mouse $CysLT_1$	Mouse $CysLT_2$
Genebank Acc.	AH119711, AF133266	AF254664	AC021992	–
Chromosome	Xq13–q21	13q14.2	XD	14
Agonist	$LTD_4 >> LTC_4 > LTE_4$	$LTD_4 = LTC_4 > LTE_4$	$LTD_4 >> LTC_4 > LTE_4$	$LTD_4 = LTC_4 > LTE_4$
Antagonist	montelukast, zafirlukast, pranlukast, BAY u9773	BAYu9773	MK571	BAYu9773
Primary coupling	$G_{\alpha q}$	$G_{\alpha q}$	$G_{\alpha q}$	$G_{\alpha q}$
Primary expression	spleen, lung, smooth muscle	heart, pulmonary vein, adrenal medulla, placenta	skin, lung	spleen, thymus, adrenal gland, small intestine

G-protein coupled receptors

CysLT1R and CysLT2R belong to the rhodopsin family of the seven-transmembrane GPCRs (116). These receptors function as GDP/GTP exchange factors (GEFs) and binding of the extracellular domain to a specific ligand induces a conformational change and promote the release of guanine nucleotide diphosphate (GDP) from the Gα subunit of a specific intracellular heterotrimeric G-protein complex (117, 118). G-proteins are members of the GTPase superfamily and are vaguely attached in the

inner plasma membrane. The Gα and Gβγ subunits are detached from each other following the release of GDP and binding of guanine nucleotide triphosphate (GTP), which more or less becomes instantly hydrolyzed and allowing the two subunits to re-associate, hence allowing the heterotrimeric complex to become once again activated (119). The G-proteins are classified based on the α-subunits, and based on their amino acid sequence similarity they are classified as four family members, termed s, i, q, and 12 (119). G-proteins are also historically classified according to their sensitivity to pertussis-toxin and ADP-ribosylation of their Gα-subunit, which renders them incapable of associating with the receptor. In general, members of the Gαi family are considered sensitive, whereas members of the Gq and G12 families are regarded pertussis toxin insensitive (120). Although both the Gα and Gβγ subunits separately can activate different effector molecules, the G-protein effector specificity is considered to be determined by the Gα subunit. For example, the Gαq and the Gαi family are coupled to receptors that all can activate phospholipase C-β (PLC-β) which catalyzes the hydrolysis of phosphatidylinositol 4,5-biphosphate (PIP_2) to generate inositol 1,4,5-triphosphate (IP_3) and 1,2-diacylglycerol (DAG), which releases Ca^{2+} from endoplasmic reticulum and activates isozymes of protein kinase C (PKC), respectively (121). The Gαs family has been shown to directly stimulate all mammalian adenylyl cyclase (AC) subtypes whereas certain members of the Gαi family inhibit some AC subtypes and their production of cyclic AMP (122). The different Gα subunits are generally considered to associate with specific receptor families, although there are some exceptions such as in the case of CysLT1R (123). LTD4-induced CysLT1R activation of the monocytic cell lines U937 and THP-1 and the intestinal epithelial cell line Int407 has demonstrated coupling to both PTX insensitive Gαq and PTX sensitive Gαi subunits (124-126). Termination of GPCR signaling, referred to as desensitization is either initiated through homologous desensitization or heterologous desensitization. The former refers to a situation in which only the activated GPCR becomes desensitized while the latter refers to desensitization of one GPCR due to activation of another, heterologous GPCR. The best characterized homologous desensitization is G-protein coupled receptor kinase (GRK)-dependent and initiated when proteins such as arrestins bind to GRK-phosphorylated GPCRs and causing either G-protein uncoupling or receptor internalization (117). In terms of CysLT1R desensitization both types have been encountered. Heterologous desensitization of CysLT1R has been observed in the monocyte/macrophage cell line U937 by series of inflammatory mediators such LTB4- induced activation of BLT1, whereas homologous desensitization and arrestin-clathrin-dependent internalization has been demonstrated in the intestinal epithelial cell line Int407 (127, 128).

Eicosanoids and cancer

Leukotriene B4

LTB4 has not only been implicated in inflammatory diseases such as asthma, chronic obstructive pulmonary disease (COPD), arthritis and IBD but also in cancers including pancreatic, breast, melanoma, lymphoma and head- and neck- carcinoma (129-134). LTB4 stimulation has been shown to promote proliferation in the colon cancer cell lines HT-29 and HCT-115 in a time- and concentration-dependent manner (135). Increased expression of BLT1 has been observed in human colon cancer tissues and the inhibition of the LTB4 signaling pathway have demonstrated reduced proliferation and induction of apoptosis in the colon cancer cell lines Caco-2 and HT-29 (136). Another study has shown that the LTB4 antagonist LY293111 can potentiate the cytotoxic and tumor growth inhibiting effects of gemcitabine in a xenograft model of colon cancer (137).

Prostaglandin E2

PGE2 is the major prostanoid found in several cancers, including CRC, and often conveys poor prognosis. The mechanisms by which PGE2 has been shown to promote epithelial tumorigenesis include 1) induction of tumor epithelial cell proliferation, survival, and migration/invasion and 2) establishment of a tumor microenvironment where tumor growth and metastatic spread is facilitated by immunosurveillance inhibition and angiogenesis induction (83).

PGE2 has been shown to increase the tumor burden in $Apc^{Min/+}$ and AOM-treated mice (138, 139). However, selective inhibition of PGE2 via deletion of *mPGES-1*, a PGE2 terminal synthase in $Apc\Delta^{14/+}$ mice significantly reduced both the size and number of intestinal tumors (140). Deletion of the *mPGES-1* gene resulted also in ~ 90% reduction in the colon tumor load of AOM-treated mice, which was associated with expansion of FoxP3-positive regulatory T cells within the colon-draining mesenteric lymph nodes (141). In addition, global *Cox-2* gene disruption and pharmacological inhibition of COX-2 have resulted in reduced intestinal tumor formation in $Apc^{Min/+}$ mice (142, 143). Accordingly, tumors were not formed in AOM-treated *Cox-2*$^{-/-}$-knockout mice. Although, genetic deletion of either *Cox-1* or *Cox-2* did not have any impact on the tumor formation in the AOM/DSS mouse model of CAC (144).

Increased expression of COX-2 has been demonstrated in human colorectal adenocarcinomas and a correlation between increased adenoma prostaniod levels and adenoma size has been established in FAP patients (10, 145). Additionally, treatment with NSAIDs and selective COX-2 inhibitors have been shown to reduce the size and number of intestinal polyps in FAP patients (146-148). Also, patients receiving the selective COX-2 inhibitor celecoxib, after colonoscopic removal of sporadic colorectal adenomas have shown diminished adenoma recurrence (149).

Increased expression of CysLT1R has been documented in several human cancers, including bladder transitional cell carcinoma (TCC), neuroblastoma, brain-, prostate-, breast-, and colorectal cancer (10, 150-154). Elevated CysLT1R tumor expression has been associated with poor prognosis in breast cancer and CRC. The expression of CysLT1R in colorectal adenocarcinoma tissues has been positively correlated with cell survival factors such as COX-2 and Bcl-xL (10). However, low nuclear CysLT1R:CysLT2R expression is considered to mediate good prognosis and higher overall survival in CRC (155). Compared to intestinal epithelial cells, higher expression level of CysLT1R (10, 156) and lower expression level of CysLT2R has been observed in colon cancer cell lines (156).

Interestingly, LTC4 mediated CysLT2R activation in intestinal epithelial cells have been shown to negatively regulate the plasma membrane expression of CysLT1R by inducing internalization of the CysLT1R:CysLT2R heterodimer complex(128). LTD4 mediated CysLT1R signaling in intestinal epithelial cells has been demonstrated to induce the expression of COX-2, β-catenin, and Bcl-2, which are positively correlated with CRC progression(157). In addition, the increased expression of β-catenin was shown to be mediated by phosphatidylinositol 3-kinase (PI3K)-GSK-3β signaling (158). Moreover, LTD_4-medited CysLT1R activation in intestinal epithelial cells via cAMP response element-binding protein (CREB) and p90 ribosomal S6 kinase ($p90^{RSK}$) signaling has been shown to promote survival and proliferation, respectively, while enabling migration via PI3K-Rac signaling (8, 9) (Figure 6).

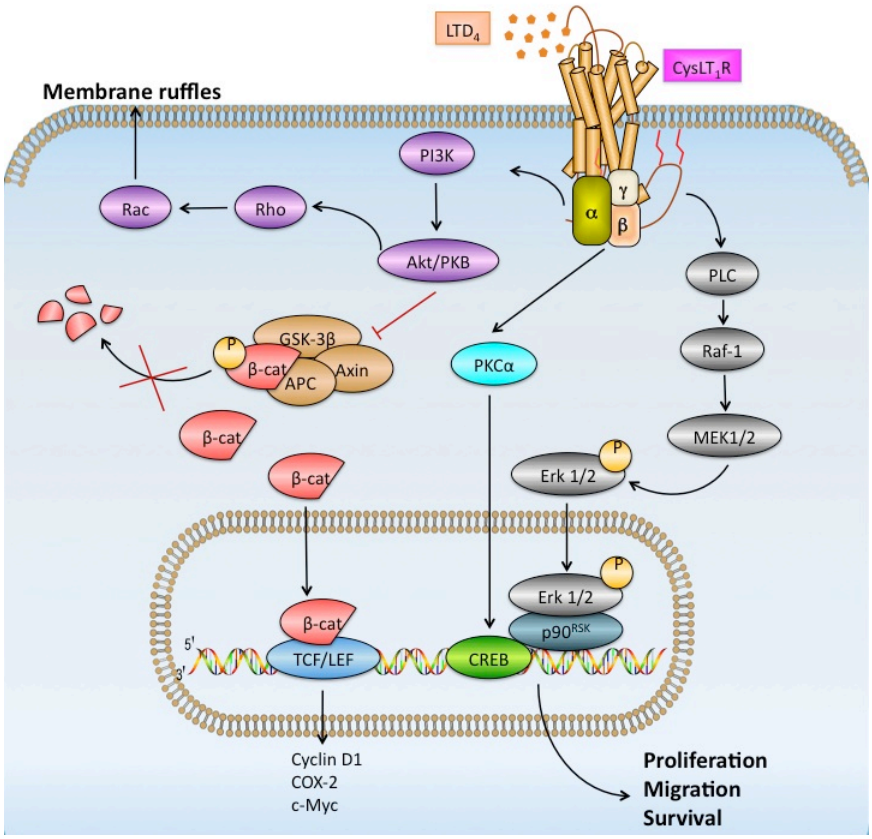

Figure 6. LTD4 signaling via CysLT1R in colorectal cancer. Adapted from Savari *et al.*, 2014.

The expression of COX-2 has been documented in various colon cancer cell lines (159) and has been shown to be upregulated via LTD4-mediated CysLT1R activation and Erk-1/2 signaling in the colon cancer cell line Caco-2, subsequently increasing the expression of the anti-apoptotic protein Bcl-2 and thus promoting survival (160). Furthermore, LTD4-mediated CysLT1R activation in the colon cancer cell line HCT-116 has been shown to induce proliferation and migration, accompanied with nuclear accumulation of β-catenin and increased transcription of the GSK-3β/β-catenin signaling pathway associated genes including *MYC* and *CCD1* (65).

A potential anti-tumor mechanism of IFN-α could be regulation of the CysLT2R promoter activity and expression (161), and LTC4-mediated CysLT1R activation has been shown to induce differentiation as demonstrated by increased intestinal alkaline phosphatase activity (156) and suppression of epidermal growth factor (EGF)-induced migration (161) in the colon cancer cell line Caco-2.

CysLT1R antagonists have been used in studies of inflammatory diseases including rheumatoid arthritis, atherosclerosis and Alzheimer's disease (162-164). The CysLT1R antagonists montelukast, pranlukast, zafirlukast and the 5-lipoxygenase inhibitor zileuton are currently used to treat asthmatic patients and have shown to reduce bronchial constriction, coughing, bronchial inflammation and the risk of asthmatic exacerbations (165). The CysLT1R antagonists have also been used in the studies of several cancers. In a variety of human urological cancer cell lines (*e.g.*, renal cell carcinoma, bladder cancer, prostate cancer, and testicular cancer) and in neuroblastoma cell lines, the CysLT1R antagonist montelukast has been shown to induce apoptosis (150-152, 166). In the colon cancer cell lines Caco-2 and SW480, the CysLT1R antagonist ZM198,615 has demonstrated reduced proliferation (167). There are several reports on dual inhibition of the COX- and LOX-pathway and augmented anti-tumor effects. A more pronounced decrease in proliferation has been observed in the colon cancer cell lines Caco-2 and HT29 when these cells were treated with the COX-2 selective inhibitor celecoxib in combination with either the 5-LOX inhibitor MK886 or CysLT1R antagonist LY171883. The combined treatment also resulted in induction of apoptosis as evidenced by caspase-3 activation and increased Bax:Bcl-2 expression ratio, whereas either of these inhibitors alone could elicit did any significant effect (168). Dual inhibition of the COX-2 and 5-LOX activity with celecoxib and AA861, respectively, has also demonstrated additional anti-tumor growth effect in a cigarette smoke-promoting mouse xenograft model of CRC. Moreover, the combined treatment resulted in greater inhibitory effect on proliferation and angiogenesis than the individual compounds (169).

Present investigation

Aim

The overall aim of the presented studies has been to investigate the role of CysLT1R in colorectal cancer *in vivo*, using different mouse models.

Materials and methods

Chemicals

The CysLT1R antagonists ZM198,615 (ICI-198,615) and montelukast were from AstraZeneca (London, England, UK) and Cayman Chemicals Co. (Ann Arbor, MI, USA), respectively. Azoxymethane (AOM) and dextran sulfate sodium (DSS) were purchased from Sigma-Aldrich Corporation (St. Louis, MO, USA) and MP Biomedicals (Santa Ana, CA, USA), respectively.

Cell culture

The human colon adenocarcinoma cell lines HCT-116 (ATCC® No. CCL-247), SW-480 (ATCC® No. CCL-228) and HT-29 (ATCC® No. HTB-38) were obtained from American Type Culture Collection (Manassas, VA, USA). The HCT-116 cells and HT-29 were cultured in McCoy's 5A medium, whereas SW-480 was cultured in RPMI 1640. The cells were maintained in a humidified incubator at 37°C with 5% CO2, in the presence of 10% fetal bovine serum (FBS) 55 μg/ml streptomycin, 55 IU/ml penicillin, and 1.5 μg/ml fungizone.

Animals

Athymic nude mice (BalbC nu/nu) were purchased from Taconic Europe A/S (Ry, Denmark) and C57BL/6J-$Apc^{Min/+}$ founder mice from The Jackson Laboratory (Bar Harbor, ME, USA). The CysLT1R knockout mice on a C57BL/6N background were kindly provided by Prof Frank Austen (Harvard Medical School, Brigham and Women's Hospital, Boston MA, USA). Single-mutant ($CysLT1R^{+/-}$, $CysLT1R^{-/-}$ and $Apc^{Min/+}$) and double-mutant mice ($CysLT1R^{+/-}$ $Apc^{Min/+}$ and $CysLT1R^{-/-}$ $Apc^{Min/+}$) and their control littermates were established and maintained at Lund University Animal Facility, Lund. The breeding colony and offspring were genotyped for

CysLT1R and/or *Min* by PCR assays. All animal experiments were conducted according D.Nr. M205-10 (Paper I), M262-12 (Paper III) or M262-13 (Paper II), approved by the Regional Ethical Committee for Animal Research at Lund University, Sweden.

Experimental setup

Female 6- to 8-week-old athymic nude mice (BalbC nu/nu) received subcutaneous injections with 2.5×10^6 HCT-116, SW-480 or HT-29 cells in two flanks per mouse (n = 6-9 mice/group). These mice received daily i.p. injections with either DMSO, ZM198,615 or montelukast (5 mg/kg) once the tumors were palpable. Moreover, mice were inoculated with either DMSO, ZM198,615 or montelukast pretreated HCT-116 cells (50 μM for 30 min) and received continued treatment from the day of inoculation. The female nude mice were sacrificed 21 days post-inoculation of colon cancer cells and had their tumors either fixed in 10% buffered formalin or snap frozen in liquid nitrogen.

Gender matched 6- to 8-week-old single mutant mice ($CysLT1R^{+/-}$ and $CysLT1R^{-/-}$) and their control littermates (C57BL/6N) received AOM (10 mg/kg, i.p.) followed one week later by two 5 day-cycles of 2% DSS in the drinking water with an intermediate recovering period of two weeks. The control mice received vehicle (0.9% NaCl, i.p.) and drinking water without DSS. The mice were sacrificed either after the second cycle of DSS or 60 days after the AOM/vehicle injection. Gender matched double-mutant mice ($CysLT1R^{+/-}$ $Apc^{Min/+}$ and $CysLT1R^{-/-}$ $Apc^{Min/+}$) and their control littermates ($Apc^{Min/+}$) were sacrificed at 14 weeks of age. Approximately half of the animals had their colon (single and double-mutant mice) and/or the small intestine (double-mutant mice) excised, fixed flat in 10% buffered formalin and subsequently evaluated for tumor count/size using a dissection microscope (2X). The entire colon and/or the distal small intestine were finally embedded in paraffin. The remaining animals had their colon and/or small intestine snap frozen in liquid nitrogen.

Immunohistochemistry

Immunostaining of sectioned (5 μm) paraffin-embedded tissues were performed using Dako automated slide stainer (Agilent Technologies Inc., Santa Clara, CA, USA) according to the manufacturer's instructions. The immunostained slides were scanned with Aperio ScanScope CS (Aperio Technologies, Inc, Vista, CA, USA) and evaluated by two independent observers in a blinded fashion. The COX-2 and 5-LOX expression were evaluated as the percentage of positive stained cells within the tumors. The subcellular localization (membraneous, cytosolic, nuclear) was evaluated for β-catenin. MUC2 expressing goblet cells, proliferative cells with incorporated bromodeoxyuridine (BrdU), and CD45-expressing infiltrating cells were estimated by counting the number of positive stained cells within the villi/crypts (n= approx. 10) and the tumor, respectively. Apoptotic cells with expression of the caspase-cleaved

product of cytokeratin 18 (M30) and vessel formation as determined by CD31 expression, were estimated by counting positive stained cells within a predetermined area in the xenograft tumors.

Flow cytometry

CysLT1R antagonist pre-treated HCT-116 cells were subjected to cell cycle and cell death measurements using propidium iodide staining and the Annexin V-PE Apoptosis Detection Kit (BD Pharmingen, San Diego, CA, USA), respectively. Single cell suspensions of colon or small intestine were obtained using gentleMACS Dissociator (Miltenyi Biotec, Auburn, CA, USA) and stained with specific conjugated antibodies to detect T-cell subpopulations of interest. Measurements were performed with FACS Calibur flow cytometer (Becton Dickinson, San Jose, CA), and analyses were performed with FCS Express 4.0 (De Novo Software, Los Angeles, CA, USA).

Cysteinyl leukotriene and prostaglandin E2 enzyme immunoassay

Media from cultured cells and animal sera were purified using solid-phase extraction Sep-Pak Vac RC (C18-500mg) cartridges from Water Corporation (Milford, MA, USA). CysLT and PG serum levels were measured with a competitive enzyme immunoassay obtained from Enzo Life Sciences (Farmingdale, NY, USA), whereas CysLT media levels were determined using an assay from Cayman Chemical Company (Ann Arbor, MI, USA). All meaurements were performed according to manufacturer's instructions.

Quantitative RT-PCR

RNeasy Plus Mini kit (Qiagen, Hilden, Germany) was used to extract RNA, that subsequently was used for cDNA synthesis using RevertAid H Minus M-MuLV Reverse Transcriptase (Thermo Scientific, Waltham, MA, USA). Maxima probe/ROX qPCR master mix and Taqman probes were used for amplification in Mx3005P thermocycler (Agilent Technologies Inc., CA, USA). Data were normalized against the house-keeping gene glyceraldehyde-3-phosphate dehydrogenase (GAPDH) and analyzed with MxPro software (Invitrogen Corp, Carlsbad, CA, USA).

Western blotting

HCT-116, SW-480 and HT-29 cell lysates were prepared as previously described (9), whereas xenograft tumors were subjected to sonication. Protein separated on precast any kD™ SDS-polyacrylamide gels (Bio-Rad Laboratories, Hercules, CA, USA) by electrophoresis were electrotransferred onto PVDF membranes. The membranes were blocked in 5% nonfat dry milk or 5% BSA in 0.05% Tween/PBS at room temperature for 1h and then incubated with primary antibody for either 1 h at room temperature or overnight at 4°C. After washing off unbound antibodies with 0.05%

TWEEN/PBS, the membranes were incubated with HRP-conjugated secondary antibodies for approximately 1 h at room temperature. Detection of proteins was made by the chemiluminescence system of Molecular Imager ChemiDoc XRS System and Image Lab software (Bio-Rad Laboratories, Hercules, CA, USA).

Proliferation assay

HCT-116 cells were seeded in triplicates in 96-well plates (1500 cells/well). Following 24 h incubation (2% FBS), the cells were treated with $CysLT_1R$ antagonists for different time points. After 90 min incubation with WST-1 reagent (Roche, Basel, Switzerland), the absorption was measured at 440 nm using the Tecan Infinite M200 plate reader.

Adhesion assay

Cells were treated with or without CysLT1R antagonists for 30 before being seeded in 12-well plates (2.0×10^5 cells/well). After 1 h incubation the cells were fixed in 4% formaldehyde for 15 min and then stained with crystal violet (5 mg/ml in 2% ethanol) for 10 min. Incubations steps longer than 30 min were made in the cell incubator, while shorter incubations were performed at room temperature, followed by (2% SDS)-PBS washing step. The staining intensity was measured at 550 nm using the Tecan Infinite M200 plate reader.

Soft agar assay

Before seeding 1.0×10^4 cells/well in medium (2% FBS) with 0.35% agarose, 0.5 % agar/well (bottom layer) was added to 6-well plates and allowed to solidify. The medium was exchanged every third day, with or without CysLT1R antagonist supplementation. Cell colonies were visualized after 14 days with 0.005% crystal violet and the ChemiDoc™ XRS+ System.

Statistical analysis

GraphPad Prism version 5.0a (GraphPad *Software* Inc., San Diego, CA, USA) was used for all statistical analyses. Paired or unpaired *t* test (Student's *t* test) was performed for comparison between two groups, while one-way or two-way ANOVA was used to compare more than two groups. P value ≤ 0.05 was considered significant. All data are presented as mean ± standard error of the mean (SEM).

Results and discussion

CysLT1R antagonists inhibit tumor growth in a xenograft model of colon cancer (Paper I)

CysLTs are pro-inflammatory lipid mediators involved in physiological conditions including mucus secretion, increased vascular permeability, eosinophil chemotaxis, and bronchoconstriction (89-92). They are also implicated in pathophysiological conditions including rheumatoid arthritis, asthma, and IBD (170-172). There is a strong correlation between the inflammatory milieu and cancer, such as IBD and colorectal cancer. In support, we have previously demonstrated that LTD4-mediated CysLT1R activation induces expression of proteins associated with colorectal cancer and promotes survival, proliferation and migration in intestinal epithelial cells (8, 9, 157). To investigate the effects of CysLT1R on colon cancer growth *in vivo*, we used the HCT-116 xenograft mouse model and two different drug administration regimens of CysLT1R antagonists (ZM198,615 or montelukast). The first regimen was established to investigate the importance of CysLT1R in tumor initiation. Mice included in this group were subcutaneously inoculated with CysLT1R antagonist-pretreated HCT-116 colon cancer cells and received continued daily treatment (5 mg/kg, i.p.). The second regimen aimed to address the role of CysLT1R in tumor progression. Mice included in this group were inoculated with non-pretreated HCT-116 cells and did not receive CysLT1R antagonist treatment (5 mg/kg, i.p.) until recordable tumor initiation. Furthermore, we performed a series of *in vitro* studies using the human colon cancer cell line HCT-116 and CysLT1R antagonists. Both CysLT1R antagonist administration regimens resulted in significantly reduced tumor size, which was accompanied with increased levels of $p21^{WAF/Cip1}$ ($P < 0.01$), cleaved caspase 3, and the caspase-cleaved product of cytokeratin 18. These data were further strengthened *in vitro* by the findings of induced apoptosis and cell cycle arrest at G1 phase in the colon cancer cell line HCT-116 after $CysLT_1R$ antagonist treatment in a dose-dependent manner, as analyzed by flow cytometry. In the same notion, montelukast has been shown to induce apoptosis in a series of human urological cancer cell lines and in neuroblastoma cell lines (150-152, 166). We were also able to detect decreased levels of VEGF ($P < 0.01$) and reduced vessel size ($P < 0.05$), the latter only in tumors established from CysLT1R antagonist pre-treated HCT-116 cells. Our results fits well with previous findings of montelukast reducing LTD4-mediated CysLT1R activation and migration of endothelial cells, a process that is required for new vessel formation (173). Furthermore, *in vitro* studies with the colon cancer cell line HCT-116 demonstrated a significant reduction in the ability of these

cells to proliferate, adhere and form colonies under the influence of CysLT1R antagonists. The ability of montelukast to inhibit tumor growth was further established by using the additional colon cancer cell lines SW-480 and HT-29 in the mouse xenograft model.

CysLT1R expression influences intestinal polyp incidence in a gender-specific manner in the $Apc^{Min/+}$ mouse model (Paper II)

High expression of CysLT1R has been observed in adenocarcinomas of colorectal cancer patients and associated with poor prognosis. In the present study we investigated the role of CysLT1R in tumorigenesis by crossing the $Apc^{Min/+}$ mice with mice lacking CysLT1R expression. The female, and not the male double mutant mice exhibited a significant ($P < 0.05$) reduction of small intestinal polyp formation in a CysLT1R gene-dosage dependent manner. A gender specific tumor reduction due to a gene deletion in $Apc^{Min/+}$ mice has been previously reported. Targeted gene deletion of *Cox-2* in the intestinal epithelium of female, but not male $Apc^{Min/+}$ mice was shown resulted to reduce intestinal polyp formation (174). The female double mutant ($CysLT_1R^{-/-}$ $Apc^{Min/+}$) phenotype was accompanied with significantly decreased intestinal polyp expression of 5-LOX and COX-2, in addition to decreased serum levels of CysLTs and PGE2. We have previously demonstrated an up-regulation of COX-2 expression in intestinal epithelial cells and colon cancer cells mediated by LTD4 stimulation of CysLT1R (157, 160). Additionally, COX-2 and 5-LOX expression in colorectal cancer specimens positively correlates with CysLT1R expression (10). We therefore speculate that global *CysLT1R* gene deletion results in decreased 5-LOX and COX expression and activity as evidenced by reduced CysLT and PGE2 serum levels. In addition, we were also able to detect reduced nuclear translocation of β-catenin within the epithelial compartment of small intestinal polyps in female double mutant ($CysLT1R^{-/-}$ $Apc^{Min/+}$) mice compared to wild-type littermates ($CysLT1R^{+/+}$ $Apc^{Min/+}$). Interestingly, deletion of *mPGES-1* that encodes the enzyme that is responsible for the production of PGE2 has been shown to inhibit nuclear translocation of β-catenin in the carcinogen azoxymethane-induced colonic lesions of mice (140). The frequency, type and site of tumor infiltrating cells have been suggested as stronger predictor of prognosis than TNM classification in colorectal cancer (175). High tumor infiltration of $CD8^+$ T cells has been positively correlated with patient survival (176). In line with this, we were able to detect an increased $CD3^+CD8^+$ T cell tumor infiltration in female double mutant ($CysLT_1R^{-/-}$ $Apc^{Min/+}$) mice compared to wild-type littermates ($CysLT_1R^{+/+}$ $Apc^{Min/+}$). Notably, PGE2 has been demonstrated to block the activity and expansion of $CD3^+CD8^+$ T cells and thereby contributing to the evasion of tumor cells from the immune surveillance (177). We speculate that decreased expression of COX-2, and subsequent

reduced production of PGE2, contributes to higher tumor infiltration of $CD8^+$ T cells and reduced nuclear translocation of β-catenin, which combined results in the reduced tumor incidence observed in female double mutant ($CysLT_1R^{-/-}$ $Apc^{Min/+}$).

The relative expression of the inflammatory receptor CysLT1 affects tumorigenesis in a colitis-associated colorectal cancer model (Paper III)

Inflammatory bowel disease (IBD), including ulcerative colitis (UC) and Crohn's disease (CD) involves chronic inflammation of the intestinal tract. The increased risk of developing colorectal cancer in patients with ulcerative colitis was recognized by Crohn *et al.* (31) and various population-based studies have estimated a 2- to 5-fold increased risk for IBD patients of developing colorectal cancer (32). To investigate the role of CysLT1R in colitis-associated colorectal cancer, we used CysLT1R knockout mice and employed the AOM/DSS-model. AOM/DSS-treated female knockout ($CysLT_1R^{-/-}$) mice demonstrated reduced tendency of polyp formation in the colon, compared to their wild-type littermates. Although, no difference could be observed in the tumor frequency in male knockout mice, they exhibited significantly decreased number of smaller tumors (≥0.5-1.0 mm, $P < 0.01$) compared to male wild-type mice. In line with previous findings of correlation between high expression of CysLT1R and 5-LOX in colorectal adenocarcinoms, we were able to detect significantly ($P < 0.05$) decreased 5-LOX tumor expression in AOM/DSS-treated female mice lacking CysLT1R expression ($CysLT_1R^{-/-}$). Also, an increased expression of 5-LOX has been demontstrated in tumors compared with normal surrounding mucosa in the colon of AOM/DSS treated mice (178). Interestingly, immunostaining revealed an increased ($P < 0.05$) expression of MUC2 in tumor surrounding villi in the colon of AOM/DSS-treated female mice lacking CysLT1R expression ($CysLT_1R^{-/-}$). MUC2 is a major structural component of the gastrointestinal mucosal barrier and reduced production by goblet cells is characteristic of pre-neoplastic lesions, referred to as aberrant crypt foci (ACF) in both rodents and humans (179-181). The pivotal role of MUC2 in colorectal cancer has been demonstrated in MUC2-deficient mice, which develop invasive tumors in the intestine and the colon (15). A significantly higher membranous:nuclear ratio of β-catenin within the epithelial tumor compartment could be observed for AOM/DSS-treated female knockout ($CysLT_1R^{-/-}$) mice. In accordance with these observations, we have previously demonstrated that LTD4 stimulation of CysLT1R induces nuclear translocation of β-catenin with subsequent increased proliferation and migration (65). Nuclear accumulation of β-catenin is readily found in late adenomas and carcinomas and a prerequisite for colorectal tumor progression (64). Increased serum levels of PGE2 were detected in female CysLT1R mutant ($CysLT_1R^{+/-}$ and $CysLT_1R^{-/-}$) mice compared to wild-type littermates. However, knockout mice have illustrated that cyclooxygenase-derived

prostanoids are not major components in colitis-associated colorectal cancer (144) but might actually have a protective role against inflammation in the colon (22, 182). In conclusion, we demonstrate that AOM/DSS treated female knockout ($CysLT_1R^{-/-}$) mice have a reduced tendency to develop tumors in the colon, which could be attributed to increased tumor epithelial membranous:nuclear ratio of β-catenin expression and increased MUC2 expression, indicative of a more differentiated phenotype.

Summary

- CysLT1R antagonists inhibit tumor growth in a xenograft model of colon cancer by impairing angiogenesis and inducing apoptosis.

- Global deletion of the *CysLT1R* affects tumorigeneis in a gender-specific manner in both the $Apc^{Min/+}$ mouse model and the AOM/DSS model of colitis-associated colorectal cancer.

Populärvetenskaplig sammanfattning

Det finns ett starkt samband mellan kronisk inflammation och cancer. Ett av de mer etablerade sambanden är den mellan kronisk inflammation i tarmen och den i Sverige tredje vanligaste cancersjukdomen, nämligen tjocktarmscancer. Risken för tjocktarmscancer korrelerar med inflammationsutbredning, varaktighet och svårighetsgrad. Den inflammatoriska processen regleras av rekryterade immunologiska celler och berörd vävnad huvudsakligen via olika signaleringsmolekyler såsom leukotriener. Dessa molekyler är pro-inflammatoriska och bidrar bland annat till vätskeansamling i samband med en inflammatorisk process. De bidrar också till muskelsammandragningar och är patologiskt förknippade i det avseendet med andningssvårigheter vid astma. Leukotriener förmedlar sin effekt via inbindning till specifika cellmottagare, s.k. receptorer. Det mest potenta leukotrienet är cysteinyl leukotriene D4 (LTD4) och medlar främst via receptorn cysteinyl leukotriene 1 (CysLT1R). Vår forskningsgrupp har tidigare funnit att patienter med koloncancer (Dukes B typ) som har ett högt tumörvävnadsuttryck av CysLT1R har sämre överlevnadsprognos jämfört med patienter med lågt uttryck. Vi har också upptäckt att en närbesläktad receptor (CysLT2R) som också finns i tumörer men har uppvisat motsatt effekt på tumörceller och därmed positiv effekt för patienten. Vi har tidigare också i cellkulturer med olika koloncancer cellinjer sett att LTD4 via CysLT1R ger en ökad cellöverlevnad och vandringsförmåga, s.k. migration som är en förutsättning för metastasering, d.v.s. spridning till andra vävnader och etablering av sekundära tumörer. Däremot har cysteinyl leukotriene-inducerad CysLT2R signalering påvisat celldifferentiering, något som förknippas med cellmognad, vävnadsstabilitet och integritet. Eftersom tumörbildningsförmågan beror på interaktion mellan tumörceller och omgivande celler och vävnader inte går att undersöka genom att studera enskilda celler i en cellkultur, har nästa givna steg varit att utföra djurstudier.

Jag har i mina avhandlingsarbeten undersökt betydelsen av CysLT1R i olika djurmodeller för tjocktarmscancer. Vi har kunnat visa att behandling av subkutana humana koloncancerceller med substanser som specifikt binder till CysLT1R och förhindrar dess aktivitet, s.k. antagonister ger reducerad tumör tillväxt i möss med bristfälligt cellulär immunsystem. Detta åtföljdes av en minskad celldelning och kärlbildning i tumörerna samt ökad celldöd. Genomisk förändring, s.k. mutation av *APC*-genen bärs av mellan 80-90% av alla koloncancer patienter samt är ansvarig för den familjära formen av tjocktarmscancer (familial adenomatous polyposis; FAP), d.v.s. *APC*-genen är en betydande faktor i den mänskliga etiologin för tjocktarmscancer. *APC*-genen är involverad i flera cellulära processer som reglerar

celltillväxt och celldelning. För att studera betydelsen av CysLT1R i utvecklingen av tjocktarmscancer hos dessa patienter använde vi oss av $Apc^{Min/+}$ musmodellen som har en mutation i *Apc*-genen, vilket möjligör bildandet av flera tumörer i huvudsakligen tunntarmen. Vi kunde särskilja en könsspecifik skillnad i tumörbildningen, som var direkt beroende av CysLT1R-genuttrycket. Honor som saknade uttryck av CysLT1R hade signifikant mindre antal av tumörer i tunntarmen, i jämförelse med honor som hade oförändrad CysLT1R-uttryck. Dessa möss hade också större tumörinfiltrat av vita blodceller, subtyp CD8+ T celler, något som är gynnande och överrensstämmer med tjocktarmscancer patienter och deras överlevnadsprognoser. Honor som saknade uttryck av CysLT1R hade också, förutom reducering av cysteinyl leukotriener såsom LTD4, även en minskning av prostaglandin E2 (PGE2) serumkoncentrationer. Detta är anmärkningsvärd med avseende på att PGE2, och det enzym som ansvarar för dess produktion (COX-2), har påvisats i större mängder hos patienter med tjocktarmscancer. Låga doser av aspirin (acetylsalicylsyra – ASA), som hämmar bildningen av prostaglandiner har också uppvisat en skyddande effekt mot tjocktarmscancer. För att vidare verifiera betydelsen av CysLT1R använde vi möss som saknade uttryck av CysLT1R och tillämpade ett väletablerat protokoll för kemisk inducering av kolit-associerad tjocktarmscancer. Dessa djur uppvisade samma tendenser men inte i samma utsträckning som de honmöss som också saknade uttryck av APC. Vårt resultat indikerar att CysLT1R är av betydelse för utvecklingen av tjocktarmscancer i möss, möjligtvis mer i samband med avsaknad av APC uttryck. Dessa resultat lyfter också fram möjligheterna med att påverka aktiviteten hos CysLT1R som alternativ terapeutiskt mål vid behandling av patienter med tjocktarmscancer.

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References

1. Hajdu SI. A note from history: landmarks in history of cancer, part 1. Cancer. 2011;117:1097-102.
2. DeVita VT, Jr., Rosenberg SA. Two hundred years of cancer research. N Engl J Med. 2012;366:2207-14.
3. Bishop JM, Weinberg RA, Scientific American inc. Scientific American molecular oncology. New York: Scientific American; 1996.
4. Hanahan D, Weinberg RA. The hallmarks of cancer. Cell. 2000;100:57-70.
5. Hanahan D, Weinberg RA. Hallmarks of cancer: the next generation. Cell. 2011;144:646-74.
6. Bernstein CN, Blanchard JF, Kliewer E, Wajda A. Cancer risk in patients with inflammatory bowel disease: a population-based study. Cancer. 2001;91:854-62.
7. Hammerbeck DM, Brown DR. Presence of immunocytes and sulfidopeptide leukotrienes in the inflamed guinea pig distal colon. Inflammation. 1996;20:413-25.
8. Paruchuri S, Broom O, Dib K, Sjolander A. The pro-inflammatory mediator leukotriene D4 induces phosphatidylinositol 3-kinase and Rac-dependent migration of intestinal epithelial cells. J Biol Chem. 2005;280:13538-44.
9. Paruchuri S, Sjolander A. Leukotriene D4 mediates survival and proliferation via separate but parallel pathways in the human intestinal epithelial cell line Int 407. J Biol Chem. 2003;278:45577-85.
10. Ohd JF, Nielsen CK, Campbell J, Landberg G, Lofberg H, Sjolander A. Expression of the leukotriene D4 receptor CysLT1, COX-2, and other cell survival factors in colorectal adenocarcinomas. Gastroenterology. 2003;124:57-70.
11. Peterson LW, Artis D. Intestinal epithelial cells: regulators of barrier function and immune homeostasis. Nat Rev Immunol. 2014;14:141-53.

12. Sancho E, Batlle E, Clevers H. Signaling pathways in intestinal development and cancer. Annual review of cell and developmental biology. 2004;20:695-723.
13. Linden SK, Sutton P, Karlsson NG, Korolik V, McGuckin MA. Mucins in the mucosal barrier to infection. Mucosal immunology. 2008;1:183-97.
14. Van der Sluis M, De Koning BA, De Bruijn AC, Velcich A, Meijerink JP, Van Goudoever JB, et al. Muc2-deficient mice spontaneously develop colitis, indicating that MUC2 is critical for colonic protection. Gastroenterology. 2006;131:117-29.
15. Velcich A, Yang W, Heyer J, Fragale A, Nicholas C, Viani S, et al. Colorectal cancer in mice genetically deficient in the mucin Muc2. Science. 2002;295:1726-9.
16. Yang K, Popova NV, Yang WC, Lozonschi I, Tadesse S, Kent S, et al. Interaction of Muc2 and Apc on Wnt signaling and in intestinal tumorigenesis: potential role of chronic inflammation. Cancer Res. 2008;68:7313-22.
17. Podolsky DK. Inflammatory bowel disease. N Engl J Med. 2002;347:417-29.
18. Kaser A, Zeissig S, Blumberg RS. Inflammatory bowel disease. Annual review of immunology. 2010;28:573-621.
19. Libioulle C, Louis E, Hansoul S, Sandor C, Farnir F, Franchimont D, et al. Novel Crohn disease locus identified by genome-wide association maps to a gene desert on 5p13.1 and modulates expression of PTGER4. PLoS genetics. 2007;3:e58.
20. Silverberg MS, Cho JH, Rioux JD, McGovern DP, Wu J, Annese V, et al. Ulcerative colitis-risk loci on chromosomes 1p36 and 12q15 found by genome-wide association study. Nature genetics. 2009;41:216-20.
21. Kabashima K, Saji T, Murata T, Nagamachi M, Matsuoka T, Segi E, et al. The prostaglandin receptor EP4 suppresses colitis, mucosal damage and CD4 cell activation in the gut. J Clin Invest. 2002;109:883-93.
22. Morteau O, Morham SG, Sellon R, Dieleman LA, Langenbach R, Smithies O, et al. Impaired mucosal defense to acute colonic injury in mice lacking cyclooxygenase-1 or cyclooxygenase-2. J Clin Invest. 2000;105:469-78.
23. Sharon P, Stenson WF. Enhanced synthesis of leukotriene B4 by colonic mucosa in inflammatory bowel disease. Gastroenterology. 1984;86:453-60.

24. Stanke-Labesque F, Pofelski J, Moreau-Gaudry A, Bessard G, Bonaz B. Urinary leukotriene E4 excretion: a biomarker of inflammatory bowel disease activity. Inflamm Bowel Dis. 2008;14:769-74.
25. Zingarelli B, Squadrito F, Graziani P, Camerini R, Caputi AP. Effects of zileuton, a new 5-lipoxygenase inhibitor, in experimentally induced colitis in rats. Agents and actions. 1993;39:150-6.
26. Bertran X, Mane J, Fernandez-Banares F, Castella E, Bartoli R, Ojanguren I, et al. Intracolonic administration of zileuton, a selective 5-lipoxygenase inhibitor, accelerates healing in a rat model of chronic colitis. Gut. 1996;38:899-904.
27. Cuzzocrea S, Rossi A, Mazzon E, Di Paola R, Genovese T, Muia C, et al. 5-Lipoxygenase modulates colitis through the regulation of adhesion molecule expression and neutrophil migration. Laboratory investigation; a journal of technical methods and pathology. 2005;85:808-22.
28. Coussens LM, Werb Z. Inflammation and cancer. Nature. 2002;420:860-7.
29. Lennard-Jones JE, Morson BC, Ritchie JK, Williams CB. Cancer surveillance in ulcerative colitis. Experience over 15 years. Lancet. 1983;2:149-52.
30. Choi PM, Zelig MP. Similarity of colorectal cancer in Crohn's disease and ulcerative colitis: implications for carcinogenesis and prevention. Gut. 1994;35:950-4.
31. Crohn UB, Rosenberg H. The sigmoidoscopic picture of chronic ulcerative colitis (non-specific). Am J Med Sci. 1925;170:220-8.
32. Guagnozzi D, Lucendo AJ. Colorectal cancer surveillance in patients with inflammatory bowel disease: What is new? World journal of gastrointestinal endoscopy. 2012;4:108-16.
33. Andersen NN, Jess T. Has the risk of colorectal cancer in inflammatory bowel disease decreased? World J Gastroentero. 2013;19:7561-8.
34. Eaden J, Abrams K, Ekbom A, Jackson E, Mayberry J. Colorectal cancer prevention in ulcerative colitis: a case-control study. Aliment Pharmacol Ther. 2000;14:145-53.
35. Rubin DT, LoSavio A, Yadron N, Huo D, Hanauer SB. Aminosalicylate therapy in the prevention of dysplasia and colorectal cancer in ulcerative colitis. Clin Gastroenterol Hepatol. 2006;4:1346-50.

36. Tang J, Sharif O, Pai C, Silverman AL. Mesalamine protects against colorectal cancer in inflammatory bowel disease. Dig Dis Sci. 2010;55:1696-703.
37. Clapper ML, Gary MA, Coudry RA, Litwin S, Chang WC, Devarajan K, et al. 5-aminosalicylic acid inhibits colitis-associated colorectal dysplasias in the mouse model of azoxymethane/dextran sulfate sodium-induced colitis. Inflamm Bowel Dis. 2008;14:1341-7.
38. Ferlay J, Shin HR, Bray F, Forman D, Mathers C, Parkin DM. Estimates of worldwide burden of cancer in 2008: GLOBOCAN 2008. Int J Cancer. 2010.
39. Munkholm P. Review article: the incidence and prevalence of colorectal cancer in inflammatory bowel disease. Aliment Pharmacol Ther. 2003;18 Suppl 2:1-5.
40. Terzic J, Grivennikov S, Karin E, Karin M. Inflammation and colon cancer. Gastroenterology. 2010;138:2101-14 e5.
41. Ullman TA, Itzkowitz SH. Intestinal inflammation and cancer. Gastroenterology. 2011;140:1807-16.
42. Redston MS, Papadopoulos N, Caldas C, Kinzler KW, Kern SE. Common Occurrence of Apc and K-Ras Gene-Mutations in the Spectrum of Colitis-Associated Neoplasias. Gastroenterology. 1995;108:383-92.
43. Tarmin L, Yin J, Harpaz N, Kozam M, Noordzij J, Jiang HY, et al. Apc Gene-Mutations in Ulcerative Colitis-Associated Dysplasias and Cancers Versus Sporadic Colon Neoplasms. Gastroenterology. 1995;108:A927-A.
44. Beckers J, de Angelis MH. Large-scale mutational analysis for the annotation of the mouse genome. Curr Opin Chem Biol. 2002;6:17-23.
45. Powell SM, Zilz N, Beazerbarclay Y, Bryan TM, Hamilton SR, Thibodeau SN, et al. Apc Mutations Occur Early during Colorectal Tumorigenesis. Nature. 1992;359:235-7.
46. Umetani N, Sasaki S, Watanabe T, Shinozaki M, Matsuda K, Ishigami H, et al. Genetic alterations in ulcerative colitis-associated neoplasia focusing on APC, K-ras gene and microsatellite instability. Jpn J Cancer Res. 1999;90:1081-7.
47. Burmer GC, Rabinovitch PS, Haggitt RC, Crispin DA, Brentnall TA, Kolli VR, et al. Neoplastic progression in ulcerative colitis: histology, DNA content, and loss of a p53 allele. Gastroenterology. 1992;103:1602-10.

48. Gooden MJ, de Bock GH, Leffers N, Daemen T, Nijman HW. The prognostic influence of tumour-infiltrating lymphocytes in cancer: a systematic review with meta-analysis. Br J Cancer. 2011;105:93-103.
49. Sinicrope FA, Rego RL, Ansell SM, Knutson KL, Foster NR, Sargent DJ. Intraepithelial effector (CD3+)/regulatory (FoxP3+) T-cell ratio predicts a clinical outcome of human colon carcinoma. Gastroenterology. 2009;137:1270-9.
50. Diederichsen AC, Hjelmborg J, Christensen PB, Zeuthen J, Fenger C. Prognostic value of the CD4+/CD8+ ratio of tumour infiltrating lymphocytes in colorectal cancer and HLA-DR expression on tumour cells. Cancer immunology, immunotherapy : CII. 2003;52:423-8.
51. Meira LB, Bugni JM, Green SL, Lee CW, Pang B, Borenshtein D, et al. DNA damage induced by chronic inflammation contributes to colon carcinogenesis in mice. J Clin Invest. 2008;118:2516-25.
52. Popivanova BK, Kitamura K, Wu Y, Kondo T, Kagaya T, Kaneko S, et al. Blocking TNF-alpha in mice reduces colorectal carcinogenesis associated with chronic colitis. J Clin Invest. 2008;118:560-70.
53. Grivennikov S, Karin E, Terzic J, Mucida D, Yu GY, Vallabhapurapu S, et al. IL-6 and Stat3 are required for survival of intestinal epithelial cells and development of colitis-associated cancer. Cancer Cell. 2009;15:103-13.
54. Rustgi AK. The genetics of hereditary colon cancer. Genes & development. 2007;21:2525-38.
55. Lockhart-Mummery P. Cancer and heredity. Lancet. 1925;1:427-9.
56. Debinski HS, Love S, Spigelman AD, Phillips RKS. Colorectal polyp counts and cancer risk in familial adenomatous polyposis. Gastroenterology. 1996;110:1028-30.
57. Groden J, Thliveris A, Samowitz W, Carlson M, Gelbert L, Albertsen H, et al. Identification and Characterization of the Familial Adenomatous Polyposis-Coli Gene. Cell. 1991;66:589-600.
58. Kinzler KW, Nilbert MC, Su LK, Vogelstein B, Bryan TM, Levy DB, et al. Identification of Fap Locus Genes from Chromosome-5q21. Science. 1991;253:661-5.
59. Nishisho I, Nakamura Y, Miyoshi Y, Miki Y, Ando H, Horii A, et al. Mutations of Chromosome-5q21 Genes in Fap and Colorectal-Cancer Patients. Science. 1991;253:665-9.

60. Levy DB, Smith KJ, Beazerbarclay Y, Hamilton SR, Vogelstein B, Kinzler KW. Inactivation of Both Apc Alleles in Human and Mouse-Tumors. Cancer Research. 1994;54:5953-8.
61. Miyoshi Y, Nagase H, Ando H, Horii A, Ichii S, Nakatsuru S, et al. Somatic mutations of the APC gene in colorectal tumors: mutation cluster region in the APC gene. Hum Mol Genet. 1992;1:229-33.
62. Clevers H. Wnt/beta-catenin signaling in development and disease. Cell. 2006;127:469-80.
63. Schneikert J, Behrens J. The canonical Wnt signalling pathway and its APC partner in colon cancer development. Gut. 2007;56:417-25.
64. Phelps RA, Chidester S, Dehghanizadeh S, Phelps J, Sandoval IT, Rai K, et al. A two-step model for colon adenoma initiation and progression caused by APC loss. Cell. 2009;137:623-34.
65. Salim T, Sand-Dejmek J, Sjolander A. The inflammatory mediator leukotriene D-4 induces subcellular beta-catenin translocation and migration of colon cancer cells. Experimental Cell Research. 2014;321:255-66.
66. Castellone MD, Teramoto H, Williams BO, Druey KM, Gutkind JS. Prostaglandin E2 promotes colon cancer cell growth through a Gs-axin-beta-catenin signaling axis. Science. 2005;310:1504-10.
67. Oshima M, Dinchuk JE, Kargman SL, Oshima H, Hancock B, Kwong E, et al. Suppression of intestinal polyposis in Apc delta716 knockout mice by inhibition of cyclooxygenase 2 (COX-2). Cell. 1996;87:803-9.
68. Sonoshita M, Takaku K, Sasaki N, Sugimoto Y, Ushikubi F, Narumiya S, et al. Acceleration of intestinal polyposis through prostaglandin receptor EP2 in Apc(Delta 716) knockout mice. Nat Med. 2001;7:1048-51.
69. Moser AR, Pitot HC, Dove WF. A Dominant Mutation That Predisposes to Multiple Intestinal Neoplasia in the Mouse. Science. 1990;247:322-4.
70. Su LK, Kinzler KW, Vogelstein B, Preisinger AC, Moser AR, Luongo C, et al. Multiple Intestinal Neoplasia Caused by a Mutation in the Murine Homolog of the Apc Gene. Science. 1992;256:668-70.
71. Fodde R, Edelmann W, Yang K, Vanleeuwen C, Carlson C, Renault B, et al. A Targeted Chain-Termination Mutation in the Mouse Apc Gene Results in Multiple Intestinal Tumors. P Natl Acad Sci USA. 1994;91:8969-73.
72. Oshima M, Oshima H, Kitagawa K, Kobayashi M, Itakura C, Taketo M. Loss of Apc Heterozygosity and Abnormal Tissue Building in

Nascent Intestinal Polyps in Mice Carrying a Truncated Apc Gene. P Natl Acad Sci USA. 1995;92:4482-6.
73. Cunningham D, Atkin W, Lenz HJ, Lynch HT, Minsky B, Nordlinger B, et al. Colorectal cancer. Lancet. 2010;375:1030-47.
74. Damin DC, Lazzaron AR. Evolving treatment strategies for colorectal cancer: A critical review of current therapeutic options. World J Gastroentero. 2014;20:877-87.
75. Sobin LH, Gospodarowicz MK, Wittekind C, International Union against Cancer., ebrary Inc. TNM classification of malignant tumours. 7th ed. Chichester, West Sussex, UK ; Hoboken, NJ: Wiley-Blackwell,; 2009. p. xx, 310 p.
76. Edwards MS, Chadda SD, Zhao Z, Barber BL, Sykes DP. A systematic review of treatment guidelines for metastatic colorectal cancer. Colorectal Dis. 2012;14:e31-e47.
77. Smith WL. The Eicosanoids and Their Biochemical-Mechanisms of Action. Biochem J. 1989;259:315-24.
78. Funk CD. Prostaglandins and leukotrienes: Advances in eicosanoid biology. Science. 2001;294:1871-5.
79. Samuelss.B. Prostaglandins. Angew Chem Int Edit. 1965;4:410-&.
80. Samuelsson B. Leukotrienes: a new class of mediators of immediate hypersensitivity reactions and inflammation. Adv Prostaglandin Thromboxane Leukot Res. 1983;11:1-13.
81. Samuelsson B. The discovery of the leukotrienes. Am J Respir Crit Care Med. 2000;161:S2-6.
82. Ferrer R, Moreno JJ. Role of eicosanoids on intestinal epithelial homeostasis. Biochemical pharmacology. 2010;80:431-8.
83. Wang D, Dubois RN. Eicosanoids and cancer. Nat Rev Cancer. 2010;10:181-93.
84. Cathcart MC, Lysaght J, Pidgeon GP. Eicosanoid signalling pathways in the development and progression of colorectal cancer: novel approaches for prevention/intervention. Cancer Metastasis Rev. 2011;30:363-85.
85. Peters-Golden M, Henderson WR. Mechanisms of disease: Leukotrienes. New England Journal of Medicine. 2007;357:1841-54.
86. Lam BK, Austen KF. Leukotriene C4 synthase: a pivotal enzyme in cellular biosynthesis of the cysteinyl leukotrienes. Prostaglandins Other Lipid Mediat. 2002;68-69:511-20.

87. Murphy RC, Gijon MA. Biosynthesis and metabolism of leukotrienes. Biochem J. 2007;405:379-95.
88. Fabre JE, Goulet JL, Riche E, Nguyen M, Coggins K, Offenbacher S, et al. Transcellular biosynthesis contributes to the production of leukotrienes during inflammatory responses in vivo. J Clin Invest. 2002;109:1373-80.
89. Chan CC, McKee K, Tagari P, Chee P, Ford-Hutchinson A. Eosinophil-eicosanoid interactions: inhibition of eosinophil chemotaxis in vivo by a LTD4-receptor antagonist. Eur J Pharmacol. 1990;191:273-80.
90. Barnes NC, Piper PJ, Costello JF. Comparative effects of inhaled leukotriene C4, leukotriene D4, and histamine in normal human subjects. Thorax. 1984;39:500-4.
91. Drazen JM, Austen KF, Lewis RA, Clark DA, Goto G, Marfat A, et al. Comparative airway and vascular activities of leukotrienes C-1 and D in vivo and in vitro. Proc Natl Acad Sci U S A. 1980;77:4354-8.
92. Marom Z, Shelhamer JH, Bach MK, Morton DR, Kaliner M. Slow-reacting substances, leukotrienes C4 and D4, increase the release of mucus from human airways in vitro. Am Rev Respir Dis. 1982;126:449-51.
93. Panettieri RA, Tan EM, Ciocca V, Luttmann MA, Leonard TB, Hay DW. Effects of LTD4 on human airway smooth muscle cell proliferation, matrix expression, and contraction In vitro: differential sensitivity to cysteinyl leukotriene receptor antagonists. American journal of respiratory cell and molecular biology. 1998;19:453-61.
94. Labat C, Ortiz JL, Norel X, Gorenne I, Verley J, Abram TS, et al. A second cysteinyl leukotriene receptor in human lung. J Pharmacol Exp Ther. 1992;263:800-5.
95. Back M, Norel X, Walch L, Gascard J, Mazmanian G, Dahlen S, et al. Antagonist resistant contractions of the porcine pulmonary artery by cysteinyl-leukotrienes. Eur J Pharmacol. 2000;401:381-8.
96. Capra V, Thompson MD, Sala A, Cole DE, Folco G, Rovati GE. Cysteinyl-leukotrienes and their receptors in asthma and other inflammatory diseases: critical update and emerging trends. Med Res Rev. 2007;27:469-527.
97. Lynch KR, O'Neill GP, Liu Q, Im DS, Sawyer N, Metters KM, et al. Characterization of the human cysteinyl leukotriene CysLT1 receptor. Nature. 1999;399:789-93.

98. Heise CE, O'Dowd BF, Figueroa DJ, Sawyer N, Nguyen T, Im DS, et al. Characterization of the human cysteinyl leukotriene 2 receptor. J Biol Chem. 2000;275:30531-6.
99. Singh RK, Gupta S, Dastidar S, Ray A. Cysteinyl leukotrienes and their receptors: molecular and functional characteristics. Pharmacology. 2010;85:336-49.
100. Martin V, Sawyer N, Stocco R, Unett D, Lerner MR, Abramovitz M, et al. Molecular cloning and functional characterization of murine cysteinyl-leukotriene 1 (CysLT(1)) receptors. Biochemical pharmacology. 2001;62:1193-200.
101. Maekawa A, Kanaoka Y, Lam BK, Austen KF. Identification in mice of two isoforms of the cysteinyl leukotriene 1 receptor that result from alternative splicing. Proc Natl Acad Sci U S A. 2001;98:2256-61.
102. Maekawa A, Austen KF, Kanaoka Y. Targeted gene disruption reveals the role of cysteinyl leukotriene 1 receptor in the enhanced vascular permeability of mice undergoing acute inflammatory responses. J Biol Chem. 2002;277:20820-4.
103. Ciana P, Fumagalli M, Trincavelli ML, Verderio C, Rosa P, Lecca D, et al. The orphan receptor GPR17 identified as a new dual uracil nucleotides/cysteinyl-leukotrienes receptor. EMBO J. 2006;25:4615-27.
104. Paruchuri S, Tashimo H, Feng C, Maekawa A, Xing W, Jiang Y, et al. Leukotriene E4-induced pulmonary inflammation is mediated by the P2Y12 receptor. J Exp Med. 2009;206:2543-55.
105. Maekawa A, Kanaoka Y, Xing W, Austen KF. Functional recognition of a distinct receptor preferential for leukotriene E4 in mice lacking the cysteinyl leukotriene 1 and 2 receptors. Proc Natl Acad Sci U S A. 2008;105:16695-700.
106. Yokomizo T, Izumi T, Chang K, Takuwa Y, Shimizu T. A G-protein-coupled receptor for leukotriene B4 that mediates chemotaxis. Nature. 1997;387:620-4.
107. Yokomizo T, Kato K, Terawaki K, Izumi T, Shimizu T. A second leukotriene B(4) receptor, BLT2. A new therapeutic target in inflammation and immunological disorders. J Exp Med. 2000;192:421-32.
108. Yokomizo T, Izumi T, Shimizu T. Leukotriene B4: metabolism and signal transduction. Arch Biochem Biophys. 2001;385:231-41.
109. Tager AM, Luster AD. BLT1 and BLT2: the leukotriene B(4) receptors. Prostaglandins Leukot Essent Fatty Acids. 2003;69:123-34.

110. Goldman DW, Goetzl EJ. Heterogeneity of human polymorphonuclear leukocyte receptors for leukotriene B4. Identification of a subset of high affinity receptors that transduce the chemotactic response. J Exp Med. 1984;159:1027-41.
111. Tonnesen MG. Neutrophil-endothelial cell interactions: mechanisms of neutrophil adherence to vascular endothelium. The Journal of investigative dermatology. 1989;93:53S-8S.
112. Sumimoto H, Takeshige K, Minakami S. Superoxide production of human polymorphonuclear leukocytes stimulated by leukotriene B4. Biochim Biophys Acta. 1984;803:271-7.
113. Rae SA, Smith MJ. The stimulation of lysosomal enzyme secretion from human polymorphonuclear leucocytes by leukotriene B4. The Journal of pharmacy and pharmacology. 1981;33:616-7.
114. Mancuso P, Nana-Sinkam P, Peters-Golden M. Leukotriene B4 augments neutrophil phagocytosis of Klebsiella pneumoniae. Infection and immunity. 2001;69:2011-6.
115. Hebert MJ, Takano T, Holthofer H, Brady HR. Sequential morphologic events during apoptosis of human neutrophils. Modulation by lipoxygenase-derived eicosanoids. J Immunol. 1996;157:3105-15.
116. Fredriksson R, Lagerstrom MC, Lundin LG, Schioth HB. The G-protein-coupled receptors in the human genome form five main families. Phylogenetic analysis, paralogon groups, and fingerprints. Molecular pharmacology. 2003;63:1256-72.
117. Bunemann M, Hosey MM. G-protein coupled receptor kinases as modulators of G-protein signalling. The Journal of physiology. 1999;517 (Pt 1):5-23.
118. Clapham DE, Neer EJ. G protein beta gamma subunits. Annual review of pharmacology and toxicology. 1997;37:167-203.
119. Morris AJ, Malbon CC. Physiological regulation of G protein-linked signaling. Physiological reviews. 1999;79:1373-430.
120. Fields TA, Casey PJ. Signalling functions and biochemical properties of pertussis toxin-resistant G-proteins. Biochem J. 1997;321 (Pt 3):561-71.
121. Exton JH. Regulation of phosphoinositide phospholipases by hormones, neurotransmitters, and other agonists linked to G proteins. Annual review of pharmacology and toxicology. 1996;36:481-509.

122. Sunahara RK, Dessauer CW, Gilman AG. Complexity and diversity of mammalian adenylyl cyclases. Annual review of pharmacology and toxicology. 1996;36:461-80.
123. Albert PR, Robillard L. G protein specificity: traffic direction required. Cellular signalling. 2002;14:407-18.
124. Capra V, Accomazzo MR, Ravasi S, Parenti M, Macchia M, Nicosia S, et al. Involvement of prenylated proteins in calcium signaling induced by LTD4 in differentiated U937 cells. Prostaglandins Other Lipid Mediat. 2003;71:235-51.
125. Hoshino M, Izumi T, Shimizu T. Leukotriene D4 activates mitogen-activated protein kinase through a protein kinase Calpha-Raf-1-dependent pathway in human monocytic leukemia THP-1 cells. J Biol Chem. 1998;273:4878-82.
126. Sjolander A, Gronroos E, Hammarstrom S, Andersson T. Leukotriene D4 and E4 induce transmembrane signaling in human epithelial cells. Single cell analysis reveals diverse pathways at the G-protein level for the influx and the intracellular mobilization of Ca2+. J Biol Chem. 1990;265:20976-81.
127. Capra V, Accomazzo MR, Gardoni F, Barbieri S, Rovati GE. A role for inflammatory mediators in heterologous desensitization of CysLT1 receptor in human monocytes. Journal of lipid research. 2010;51:1075-84.
128. Parhamifar L, Sime W, Yudina Y, Vilhardt F, Morgelin M, Sjolander A. Ligand-induced tyrosine phosphorylation of cysteinyl leukotriene receptor 1 triggers internalization and signaling in intestinal epithelial cells. PLoS One. 2010;5:e14439.
129. Hicks A, Monkarsh SP, Hoffman AF, Goodnow R, Jr. Leukotriene B4 receptor antagonists as therapeutics for inflammatory disease: preclinical and clinical developments. Expert opinion on investigational drugs. 2007;16:1909-20.
130. Earashi M, Noguchi M, Tanaka M. In vitro effects of eicosanoid synthesis inhibitors in the presence of linoleic acid on MDA-MB-231 human breast cancer cells. Breast Cancer Res Treat. 1996;37:29-37.
131. Okano-Mitani H, Ikai K, Imamura S. Human melanoma cells generate leukotrienes B4 and C4 from leukotriene A4. Arch Dermatol Res. 1997;289:347-51.
132. Bittner S, Wielckens K. Glucocorticoid-induced lymphoma cell growth inhibition: the role of leukotriene B4. Endocrinology. 1988;123:991-1000.

133. el-Hakim IE, Langdon JD, Zakrzewski JT, Costello JF. Leukotriene B4 and oral cancer. Br J Oral Maxillofac Surg. 1990;28:155-9.
134. Tong WG, Ding XZ, Hennig R, Witt RC, Standop J, Pour PM, et al. Leukotriene B4 receptor antagonist LY293111 inhibits proliferation and induces apoptosis in human pancreatic cancer cells. Clinical Cancer Research. 2002;8:3232-42.
135. Bortuzzo C, Hanif R, Kashfi K, Staiano-Coico L, Shiff SJ, Rigas B. The effect of leukotrienes B and selected HETEs on the proliferation of colon cancer cells. Biochim Biophys Acta. 1996;1300:240-6.
136. Ihara A, Wada K, Yoneda M, Fujisawa N, Takahashi H, Nakajima A. Blockade of leukotriene B4 signaling pathway induces apoptosis and suppresses cell proliferation in colon cancer. J Pharmacol Sci. 2007;103:24-32.
137. Hennig R, Ding XZ, Tong WG, Witt RC, Jovanovic BD, Adrian TE. Effect of LY293111 in combination with gemcitabine in colonic cancer. Cancer Lett. 2004;210:41-6.
138. Wang D, Wang H, Shi Q, Katkuri S, Walhi W, Desvergne B, et al. Prostaglandin E(2) promotes colorectal adenoma growth via transactivation of the nuclear peroxisome proliferator-activated receptor delta. Cancer Cell. 2004;6:285-95.
139. Kawamori T, Uchiya N, Sugimura T, Wakabayashi K. Enhancement of colon carcinogenesis by prostaglandin E2 administration. Carcinogenesis. 2003;24:985-90.
140. Nakanishi M, Montrose DC, Clark P, Nambiar PR, Belinsky GS, Claffey KP, et al. Genetic deletion of mPGES-1 suppresses intestinal tumorigenesis. Cancer Res. 2008;68:3251-9.
141. Nakanishi M, Menoret A, Tanaka T, Miyamoto S, Montrose DC, Vella AT, et al. Selective PGE(2) suppression inhibits colon carcinogenesis and modifies local mucosal immunity. Cancer Prev Res (Phila). 2011;4:1198-208.
142. Jacoby RF, Seibert K, Cole CE, Kelloff G, Lubet RA. The cyclooxygenase-2 inhibitor celecoxib is a potent preventive and therapeutic agent in the min mouse model of adenomatous polyposis. Cancer Res. 2000;60:5040-4.
143. Chulada PC, Thompson MB, Mahler JF, Doyle CM, Gaul BW, Lee C, et al. Genetic disruption of Ptgs-1, as well as Ptgs-2, reduces intestinal tumorigenesis in Min mice. Cancer Res. 2000;60:4705-8.

144. Ishikawa TO, Herschman HR. Tumor formation in a mouse model of colitis-associated colon cancer does not require COX-1 or COX-2 expression. Carcinogenesis. 2010;31:729-36.
145. Yang VW, Shields JM, Hamilton SR, Spannhake EW, Hubbard WC, Hylind LM, et al. Size-dependent increase in prostanoid levels in adenomas of patients with familial adenomatous polyposis. Cancer Res. 1998;58:1750-3.
146. Giardiello FM, Hamilton SR, Krush AJ, Piantadosi S, Hylind LM, Celano P, et al. Treatment of colonic and rectal adenomas with sulindac in familial adenomatous polyposis. N Engl J Med. 1993;328:1313-6.
147. Higuchi T, Iwama T, Yoshinaga K, Toyooka M, Taketo MM, Sugihara K. A randomized, double-blind, placebo-controlled trial of the effects of rofecoxib, a selective cyclooxygenase-2 inhibitor, on rectal polyps in familial adenomatous polyposis patients. Clin Cancer Res. 2003;9:4756-60.
148. Steinbach G, Lynch PM, Phillips RK, Wallace MH, Hawk E, Gordon GB, et al. The effect of celecoxib, a cyclooxygenase-2 inhibitor, in familial adenomatous polyposis. N Engl J Med. 2000;342:1946-52.
149. 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.
150. Matsuyama M, Funao K, Hayama T, Tanaka T, Kawahito Y, Sano H, et al. Relationship between cysteinyl-leukotriene-1 receptor and human transitional cell carcinoma in bladder. Urology. 2009;73:916-21.
151. Matsuyama M, Hayama T, Funao K, Kawahito Y, Sano H, Takemoto Y, et al. Overexpression of cysteinyl LT1 receptor in prostate cancer and CysLT1R antagonist inhibits prostate cancer cell growth through apoptosis. Oncol Rep. 2007;18:99-104.
152. Sveinbjornsson B, Rasmuson A, Baryawno N, Wan M, Pettersen I, Ponthan F, et al. Expression of enzymes and receptors of the leukotriene pathway in human neuroblastoma promotes tumor survival and provides a target for therapy. FASEB J. 2008;22:3525-36.
153. Zhang WP, Hu H, Zhang L, Ding W, Yao HT, Chen KD, et al. Expression of cysteinyl leukotriene receptor 1 in human traumatic brain injury and brain tumors. Neurosci Lett. 2004;363:247-51.
154. Magnusson C, Liu J, Ehrnstrom R, Manjer J, Jirstrom K, Andersson T, et al. Cysteinyl leukotriene receptor expression pattern affects migration of breast cancer cells and survival of breast cancer patients. Int J Cancer. 2011;129:9-22.

155. Magnusson C, Mezhybovska M, Lorinc E, Fernebro E, Nilbert M, Sjolander A. Low expression of CysLT1R and high expression of CysLT2R mediate good prognosis in colorectal cancer. Eur J Cancer. 2010;46:826-35.
156. Magnusson C, Ehrnstrom R, Olsen J, Sjolander A. An increased expression of cysteinyl leukotriene 2 receptor in colorectal adenocarcinomas correlates with high differentiation. Cancer Res. 2007;67:9190-8.
157. Ohd JF, Wikstrom K, Sjolander A. Leukotrienes induce cell-survival signaling in intestinal epithelial cells. Gastroenterology. 2000;119:1007-18.
158. Mezhybovska M, Wikstrom K, Ohd JF, Sjolander A. The inflammatory mediator leukotriene D4 induces beta-catenin signaling and its association with antiapoptotic Bcl-2 in intestinal epithelial cells. J Biol Chem. 2006;281:6776-84.
159. Parker J, Kaplon MK, Alvarez CJ, Krishnaswamy G. Prostaglandin H synthase expression is variable in human colorectal adenocarcinoma cell lines. Exp Cell Res. 1997;236:321-9.
160. Wikstrom K, Ohd JF, Sjolander A. Regulation of leukotriene-dependent induction of cyclooxygenase-2 and Bcl-2. Biochem Biophys Res Commun. 2003;302:330-5.
161. Magnusson C, Bengtsson AM, Liu M, Liu J, Ceder Y, Ehrnstrom R, et al. Regulation of cysteinyl leukotriene receptor 2 expression--a potential anti-tumor mechanism. PLoS One. 2011;6:e29060.
162. Shiota N, Shimoura K, Okunishi H. Pathophysiological role of mast cells in collagen-induced arthritis: study with a cysteinyl leukotriene receptor antagonist, montelukast. Eur J Pharmacol. 2006;548:158-66.
163. Mueller CF, Wassmann K, Widder JD, Wassmann S, Chen CH, Keuler B, et al. Multidrug resistance protein-1 affects oxidative stress, endothelial dysfunction, and atherogenesis via leukotriene C4 export. Circulation. 2008;117:2912-8.
164. Lai J, Hu M, Wang H, Hu M, Long Y, Miao MX, et al. Montelukast targeting the cysteinyl leukotriene receptor 1 ameliorates Abeta1-42-induced memory impairment and neuroinflammatory and apoptotic responses in mice. Neuropharmacology. 2014;79:707-14.
165. Bateman ED, Hurd SS, Barnes PJ, Bousquet J, Drazen JM, FitzGerald M, et al. Global strategy for asthma management and prevention: GINA executive summary. Eur Respir J. 2008;31:143-78.

166. Matsuyama M, Yoshimura R. Cysteinyl-leukotriene1 receptor is a potent target for the prevention and treatment of human urological cancer. Mol Med Report. 2010;3:245-51.
167. Paruchuri S, Mezhybovska M, Juhas M, Sjolander A. Endogenous production of leukotriene D4 mediates autocrine survival and proliferation via CysLT1 receptor signalling in intestinal epithelial cells. Oncogene. 2006;25:6660-5.
168. Cianchi F, Cortesini C, Magnelli L, Fanti E, Papucci L, Schiavone N, et al. Inhibition of 5-lipoxygenase by MK886 augments the antitumor activity of celecoxib in human colon cancer cells. Mol Cancer Ther. 2006;5:2716-26.
169. Ye YN, Wu WK, Shin VY, Bruce IC, Wong BC, Cho CH. Dual inhibition of 5-LOX and COX-2 suppresses colon cancer formation promoted by cigarette smoke. Carcinogenesis. 2005;26:827-34.
170. Nicosia S, Capra V, Rovati GE. Leukotrienes as mediators of asthma. Pulm Pharmacol Ther. 2001;14:3-19.
171. Fauler J, Thon A, Tsikas D, von der Hardt H, Frolich JC. Enhanced synthesis of cysteinyl leukotrienes in juvenile rheumatoid arthritis. Arthritis Rheum. 1994;37:93-7.
172. Stenson WF. Role of eicosanoids as mediators of inflammation in inflammatory bowel disease. Scand J Gastroenterol Suppl. 1990;172:13-8.
173. Yuan YM, Fang SH, Qian XD, Liu LY, Xu LH, Shi WZ, et al. Leukotriene D4 stimulates the migration but not proliferation of endothelial cells mediated by the cysteinyl leukotriene cyslt(1) receptor via the extracellular signal-regulated kinase pathway. J Pharmacol Sci. 2009;109:285-92.
174. Cherukuri DP, Ishikawa TO, Chun P, Catapang A, Elashoff D, Grogan TR, et al. Targeted Cox2 gene deletion in intestinal epithelial cells decreases tumorigenesis in female, but not male, Apc(Min/+) mice. Molecular oncology. 2014;8:169-77.
175. Galon J, Costes A, Sanchez-Cabo F, Kirilovsky A, Mlecnik B, Lagorce-Pages C, et al. Type, density, and location of immune cells within human colorectal tumors predict clinical outcome. Science. 2006;313:1960-4.
176. Naito Y, Saito K, Shiiba K, Ohuchi A, Saigenji K, Nagura H, et al. CD8+ T cells infiltrated within cancer cell nests as a prognostic factor in human colorectal cancer. Cancer Res. 1998;58:3491-4.
177. Kalinski P. Regulation of immune responses by prostaglandin E2. J Immunol. 2012;188:21-8.

178. Khor TO, Huang MT, Prawan A, Liu Y, Hao X, Yu S, et al. Increased susceptibility of Nrf2 knockout mice to colitis-associated colorectal cancer. Cancer Prev Res (Phila). 2008;1:187-91.
179. Otori K, Sugiyama K, Hasebe T, Fukushima S, Esumi H. Emergence of adenomatous aberrant crypt foci (ACF) from hyperplastic ACF with concomitant increase in cell proliferation. Cancer Res. 1995;55:4743-6.
180. Siu IM, Pretlow TG, Amini SB, Pretlow TP. Identification of dysplasia in human colonic aberrant crypt foci. Am J Pathol. 1997;150:1805-13.
181. Pretlow TP, Edelmann W, Kucherlapati R, Pretlow TG, Augenlicht LH. Spontaneous aberrant crypt foci in Apc1638N mice with a mutant Apc allele. Am J Pathol. 2003;163:1757-63.
182. Ishikawa TO, Oshima M, Herschman HR. Cox-2 deletion in myeloid and endothelial cells, but not in epithelial cells, exacerbates murine colitis. Carcinogenesis. 2011;32:417-26.