Signalling and trafficking of the cysteinyl leukotriene receptors in intestinal epithelial cells

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Abstract

Inflammation is a response to injury or pathogen invasion. A large proportion of the body's immune system is centred in the gastrointestinal tract (GI). Prolonged inflammatory conditions of the GI have been suggested to increase the risk for developing colon cancer.

The cysteinyl leukotrienes (CysLTs), LTC4, LTD4 and LTE4 are inflammatory mediators that can bind to four known receptors, two of which are CysLT1R and CysLT2R. Inhibitors of the CysLT1R are currently used in the clinic as asthma medication. LTD4 has been shown to induce cell proliferation, migration and survival of non-transformed intestinal epithelial cells (Int407) via the CysLT1R. These mechanisms are often used by cancer cells to survive and spread. Furthermore, increased expression of the CysLT1R in colon cancer patient material is correlated with a poorer survival prognosis. Conversely, increased expression of the CysLT2R correlates with a better survival prognosis. The aim of this thesis was therefore to explore the signalling and trafficking of the CysLT1R and CysLT2R. Our results demonstrate that LTD4 via the CysLT1R can activate the enzyme, cPLA2-alpha. This enzyme releases arachidonic acid, the precursor of CysLTs, from the cell membranes upon activation. One major regulatory mechanism of GPCR signalling is their internalization from the cell membrane upon activation. We demonstrate how LTD4 mainly internalizes the CysLT1R and accumulates this receptor at the nuclear membrane and that LTC4 internalizes both the CysLT1R and CysLT2R. This information is valuable in developing potential drug targets against CysLT1 and CysLT2 in cancer and inflammation.

Key words: Cysteinyl leukotriene receptors, cytosolic phospholipase A2, trafficking, inflammation, colon cancer

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Signature Ladan Parhamifar Date 081215

For my parents

Nothing shocks me. I'm a scientist.
Harrison Ford (1942 -), as Indiana Jones

The highest result of education is tolerance.
Helen Keller (1880 - 1968), 'Optimism,' 1903

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LIST OF PAPERS

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. **Parhamifar L, Jeppsson B, Sjölander A.**
Activation of cPLA2 is required for leukotriene D4-induced proliferation in CRC cells. Carcinogenesis. 2005 Nov; 26(11): 1988-98.

II. **Parhamifar, L, Yudina, Y, Vilhardt, F and Sjölander, A**
Nuclear trafficking and signalling of the G-protein coupled receptor, $CysLT_1$ in intestinal epithelial cells ***(Manuscript)***

III. **Parhamifar L, Vilhardt F, Mögerlin M and Sjölander A**
Co-dependent localization and ligand specific trafficking of Cysteinyl Leukotriene receptors ***(Manuscript)***

LIST OF ABBREVIATIONS

AA	arachidonic acid
ADP	adenosine 5′-diphosphate
APC	adenomatous polyposis coli
ATP	adenosine 5′-triphosphate
BSA	bovine serum albumin
cAMP	Cyclic adenosine mono phosphate
CD	Crohn's Disease
COX	Cyclooxygenase
CRC	Colorectal cancer
CREB	cAMP response element binding
CysLT	Cysteinyl leukotriene
$CysLT_1R$	Cysteinyl Leukotriene 1 receptor
$CysLT_2R$	Cysteinyl Leukotriene 2 receptor
ER	Endoplasmatic reticulum
FAP	Familial adenomatous polyposis
FLAP	Five Lipoxygenase Activating Protein
GDP	Guanosine diphosphate
GI	Gastrointestinal
GPCR	G-protein coupled receptor
HNPCC	Hereditary non-polypus colorectal cancer
IBD	Inflammatory bowel disease
LO	Lipoxygenase
LT	Leukotriene
MAPK	Mitogen-activated protein kinase
NFκB	Nuclear Factor κB
NLS	Nuclear localization signal
PBS-T	Phosphate buffer saline – Tween
PG	Prostaglandin
PI	Phosphoinositol
PK	Protein kinase
PL	Phospholipase
PLA_2	Phospholipase A_2
PPAR-γ	Peroxisome Proliferator Activated Receptor- γ
PTX	Pertussis toxin
RAMP	Receptor activity modifying protein
RGS	Regulator of G-protein signalling
TCF	T cell factor
TNF-α	Tumour necrosis factor α
TRAF	TNF receptor associated factor
UC	Ulcerative colitis

INTRODUCTION

Inflammatory responses are designated to protect the host from injuries and / or foreign invasion. The colon houses 300-500 species of bacteria, responsible for producing vitamins and other important products from food transversing the digestive system. The bacteria are prevented from entering the rest of the body by a single layer of intestinal epithelial cells, this barrier functions as the first line of defence against foreign invaders. Due to its large number of bacteria the colon maintains a low level of inflammation. An imbalance of this inflammatory state has been suggested as a possible cause of inflammatory bowel disease (IBD). Prolonged inflammatory conditions arise when the inflammatory response fails to resolve the injury, leading to continuous recruitment of inflammatory cells and inflammatory mediators to the site of injury. This continuous inflammatory response leads to tissue damage, such as the disruption of the epithelial barrier. These responses are thought to be the pre disposition to colorectal cancer.

Leukotrienes are lipid mediators produced by inflammatory cells and implicated in various inflammatory responses. High levels of leukotrienes are found in patients suffering from IBD. In intestinal epithelial cells Leukotriene D_4 (LTD_4) can induce cell growth, increase cell survival and induce cell migration by regulating various enzymes and proteins shown to be involved in cancer progression and development. LTD_4 elicits these effects through the Cysteinyl leukotriene receptor 1 ($CysLT_1R$). However, leukotrienes can bind to four different G-protein coupled receptors (GPCRs), the work in this thesis fouses on two of the best characterized CysLTRs; the $CysLT_1R$ and the $CysLT_2R$. The balance between the two first receptors has been suggested to play a role in the prognosis of colorectal cancer patients. Increased $CysLT_1$ expression correlates with a poor survival rate, whereas increased $CysLT_2$ correlates with a better prognosis.

With this in mind, the aim of the work in this thesis has been to investigate the cysteinyl leukotriene receptors $CysLT_1$ and $_2$ signalling and their regulation in particular the trafficking.

BACKGROUND

1. The intestinal epithelium

The small and large intestine are the last part of the gastrointestinal (GI) tract. In the small intestine food components such as fats, proteins and carbohydrates are broken down. The nutrient components are then transferred to the bloodstream. The large intestine absorbs the remaining water and removes the waste products (1,2).

The intestinal epithelium consists of a single layer of epithelial cells(3). They provide a barrier for the indigestible components and the gut microflora, keeping these within the lumen of the intestine.

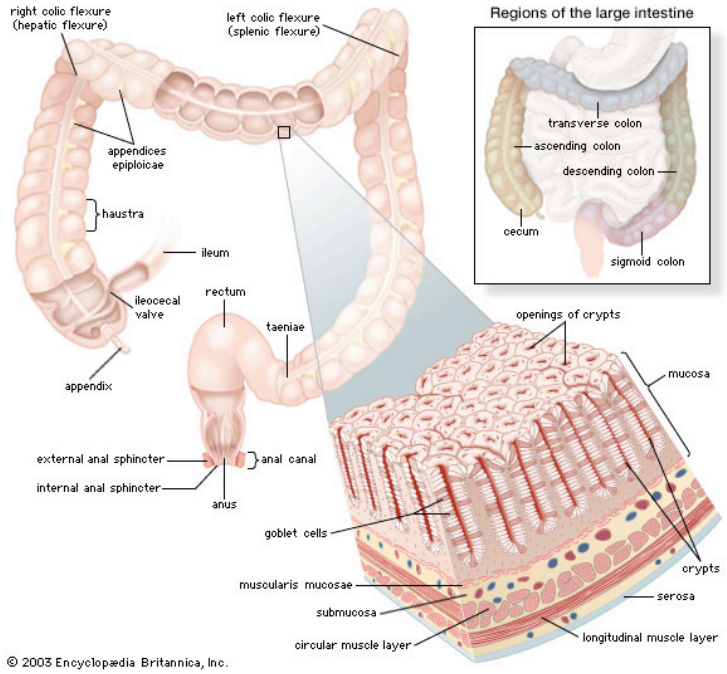

Figure1. The large intestine.

In the lining of the mammalian intestine different classes of epithelial cells termed goblet, endocrine and paneth cells can be found. Paneth cells are only found in the small intestine and constitute one of the differences between the small and large intestine. Whilst the goblet cells secrete protective mucins, the

endocrine cells secrete various gut hormones and the paneth cells secrete anti-bacterial proteins (4-6). The majority of cells are the absorptive cells are termed enterocytes (small intestine) or colonocytes (large intestine), and are positioned on a basement membrane, where the intra epithelial lymphocytes can be found migrating in and out of the intestinal epithelium.

The small intestine consists of villi and crypts whilst the large intestine consists only of crypts (3,5) (Fig.2). The villi in the small intestine mainly consist of enterocytes. At the bottom of the crypts in the small intestine reside the stem cells and the paneth cells. The paneth cells occupy the three first positions of the crypt whilst the stem cells are positioned fourth. New cells that are made at the bottom of the crypts by the stem cells, migrate up to the villi while dividing and differentiating into specialised intestinal epithelial cells (Fig.2) (4,5).

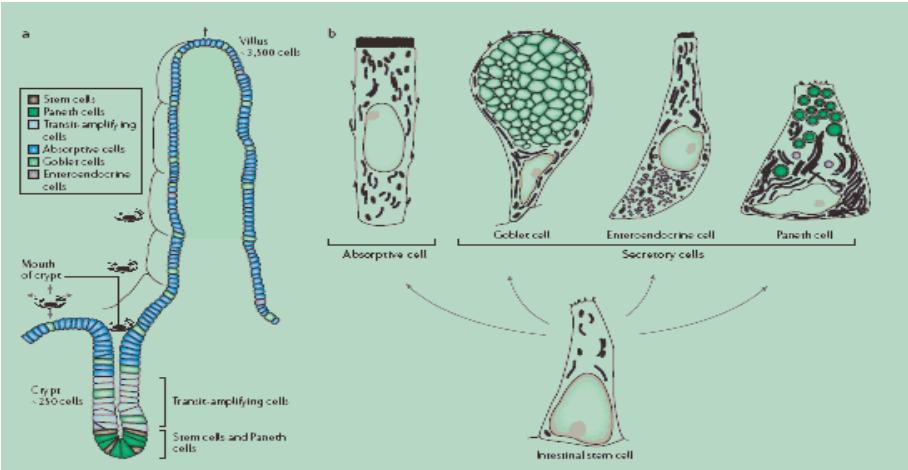

Figure2. Cells of the small intestine (Crosnier, Nature Publishing group, 2006)

Cells in transit divide three to four times before they differentiate into mature cells. Once the cells have reached the top of the villi they undergo apoptosis and sloth off in to the lumen (6). In the colon, proliferative cells

occupy two thirds of the crypt and the top third consists of the differentiated cells.

Renewal of the epithelium in the small intestine takes place every 4-6 days whilst turnover of the colonic epithelium can take 3-8 days. This high regenerative potential is what makes the intestine so fascinating but it is also its achilles heal as dys-regulation of this system has dangerous outcomes (4,5). Colonisation of the gastrointestinal tract begins after birth and the intestinal tract ends up with between 300-500 different bacterial species. The stomach and the small intestine only have a few species of bacteria but the in the colon the microflora outnumber host eukaryotic cells by 10 fold (7). The colonisation of the colon is affected by the environment and the food that the baby first eats. The first bacteria to colonise the colon can decide the gene expression patterns in the epithelial cells and create a more favourable environment for themselves and inhibit the growth of other bacteria. The normal microflora consists of mainly bacteria a few viruses and fungi (8). This normal intestinal flora is essential for the function of the intestine, however some of these bacteria are potentially pathogenic and can cause infections if the epithelial barrier has been disrupted (9). Therefore, due to its commensal bacteria the colon always produces a low level of inflammation (immune surveillance) to be able to distinguish between pathogens and “normal” commensal bacteria. This is accomplished by the existence of intra epithelial immune cells such as macrophages and dendritic cells as well as the Gastrointestinal Associated Lympoid Tissue (GALT) are lymphoid like sections, important in facilitating immune surveillance along the GI tract, which consist immune cells, such as dendritic cells, T and B lymphocytes. In the small intestine the GALT is known as the Peyer's patches. M cells are specialised epithelial cells that are located on top of the Peyer’s Patches. The M cells have loose intercellular binding, allowing the intestinal microflora easy access to the underlying lymphoid tissue. Dendritic cells present in the Payers Patches process the microbes they come into contact with and present

them to the T lymphocytes. In other GALT along the GI tract, the dendritic cells can sample antigens directly from the intestinal lumen, or receive microbes which have transversed the intestinal epithelial cells (10,11).

Specialised membrane and intracellular receptors, the Toll-like receptors (TLRs) and the NOD or NOD-like receptors (NLRs), respectively, are responsible for recognition of the microbial antigens also known as pathogen associated molecular patterns (PAMPS). These PAMPs induce tolerance towards the normal commensal bacteria through stimulating signalling pathways through the TLRs, NODs and NLRs. However dysregulation of the tolerogenic signalling pathways, for example through receptor mutation can lead to the development of prolonged or chronic inflammation (12-14).

Inflammation is a response to injury or pathogen invasion. Under normal conditions the initiation of inflammation also includes signals for the termination and resolution of inflammation (15-18). Prolonged inflammatory conditions arise when the stimulus for the acute state of inflammation is not terminated (8,19) leading to the development of inflammatory bowel disease (IBD) (20).

2. Inflammatory bowel disease

IBD is an umbrella term for several conditions (collagenous colitis, Lymphocytic colitis, Ischemic colitis, Behcet's colitis, infective colitis, intermediate colitis, diversion colitis) however there are two major conditions, ulcerative colitis (UC) and Crohn's disease (CD) (21). Even though it is difficult to compare studies geographically due to methodological differences it is suggested that the incidence of IBD is higher in developed countries(22). Patients suffering from IBD often more vulnerable to other chronic inflammatory conditions. Currently three dispositions are hypothesised to be required for the development of IBD: 1) genetic factors, for example mutations to proteins involved in immune surveillance; 2) luminal factors such

as the microflora and food antigens, for example a low fibre diet is linked to the development of IBD; and 3) environmental factors for example smoking increases the risk for the development of CD (21).

The two major conditions of IBD have similarities but also major differences. CD can affect any part of the GI tract, displaying typical discontinuous transmural inflammation and is associated with a T helper cell -1 response, over-production of IL-12/IL-23 and IFN-γ. Research has also identified mutations in the NOD2 protein as being a cause for CD in a sub-population of patients (23,24). UC on the other hand primarily affects the colon and extending rectum with the inflammation continuous and confined to the mucosa and sub mucosa, is mainly a T helper cell -2 response, mediated by an over-production of IL-13. Interestingly smoking increases the risk for CD whilst providing a protective factor against UC (7,14).

Despite the differences in the two different conditions, UC and CD also share many common features. In both cases inflammation causes mucosal destruction, which leads to loss of mucosal barrier and absorptive function. These two events have similar symptoms, such as abdominal pain and bloody diarrhoea. Furthermore both UC and CD have been associated with alterations in STAT-3 and NKX2-3. Various mouse models demonstrate an important role for the commensal bacteria in IBD (9,14,23,25).

Current non-invasive treatments for IBD mainly centre around the inhibition of the dysregulated inflammatory process. Commonly 5-aminosalicylates are used to dampen the inflammation (26) either alone or in combination with corticosteroids, which are more immunosuppressive drugs (27). However, tolerance can develop, therefore in the case of Crohn's disease several chimeric antibodies have been developed which bind to tumour necrosis factor-α (TNF-α), a major cytokine and driving factor behind IBD. Patients receiving this treatment can also unfortunately relapse (28). Thus,

ultimately, the only cure to date, (which is only possible in ulcerative colitis) is surgical resection (29).

3. Colon cancer

Colorectal cancer (CRC) is the third most common form of cancer in the western world (World health organization 2007). most common malignancy of the GI, with the overall survival rate lower that 50% (30). CRC is the second leading cause of cancer related deaths in the United States. In Sweden 5000 new cases of CRC are diagnosed every year (Swedish National board of Health and Disease, 1998). Most, if not all, malignant colorectal tumours (carcinomas) arise from pre-existing benign tumours (adenomas) (Sugarbaker et al., 1985). The rate of deaths caused by CRC can be and has been reduced by early detection with colonoscopy and testing of stool samples (31). Various factors have been suggested to increase the risk for developing CRC such as; cancer elsewhere in the body, colorectal polyps, CD, family history of CRC and UC (32). Low fibre, high fat diets and smoking have also been suggested to be risk factors for developing CRC. Genetic predisposition increases the chance of developing CRC, however the majority of cases occur sporadically (33). The loss of tumour suppressor genes which drive the sporadic adenoma carcinoma have been proposed to be a contributing factor (33). The three major carcinogenic pathways that lead to sporadic CRC and colitis associated CRC are; chromosomal instability, microsatelite instability and hyper methylation. Hyper methylation of promoter regions of cell cycle(32), DNA repair and cell adhesion genes, leads to silencing of these genes and thereby promotes CRC. In sporadic CRC the dysplastic precursor is a discrete focus of neoplasia, the adenomatous polyp that can be removed. The majority of spontaneous colorectal cancers (about 85%) are the results of chromosomal instability, the rest are due to microsatelite instability (MSI) or failure of the mismatch repair system (34,35). Both of these cases lead to the accumulation of mutations which

eventually could become carcinogenic. Chromosomal instability leads to abnormal chromosomal segregation and abnormal DNA content and eventually loss of chromosomal material and loss of function of tumour suppressor genes such as adenomatous polyposis coli (APC) and p53 (a key regulator of the cell cycle)(36). This results in activation of proto-oncogenes, such as c-myc and cyclin D1. In microsatelite instability, the loss of DNA miss match repair genes leads to loss of colonic homeostasis and neoplastic growth. Mutations in the RAS/RAF pathway, the p53 pathway, and several other genes/pathways drive tumour progression towards malignancy and metastasis (32).

Genetic predisposition to colorectal cancer depends on the presence or absence of polyps. Patients with hereditary non-polyposis colorectal cancer have an inherited mutation in an allele of a DNA mismatch repair gene(37). Patients with familial adenomatous polyposis (FAP) have a mutation in the APC gene. This pathway however is altered in approximately 95% of CRCs. FAP patients are characterised by the early onset of adenomatous colorectal polyps in the large intestine (38).

4. Colon cancer and Inflammatory Bowel Disease

The link between cancer and inflammation, has long been suggested and dates back to Virchow in 1863. IBD is one of three high risk factors for developing CRC, as patients with UC develop colorectal cancer 10 years earlier than patients with sporadic colorectal cancer (39). The other two high risk factors are having a genetic predisposition namely familial adenomatous polyposis (FAP) and hereditary non-polypus colorectal cancer (HNPCC) (32,39,40).

Dysplasia in IBD can be flat, multifocal, localised or diffuse, with the duration and surface affected by colitis increasing the risk for developing CRC (32). In sporadic CRC the cancer progresses from adenoma to carcinoma, whilst in IBD induced CRC, the progression is from inflammation to dysplasia

and then carcinoma (41). Colitis associated CRC affects individuals at a young age and has a more proximal distribution in the colon.

There is a lot of evidence to support the link between IBD and CRC. Tumours have been observed to behave very similarly to wounds that fail to heal, since they surround themselves with a milieu similar to that of a chronic inflammatory state, which for example gives rise to the production of matrix metalloproteinases, tissue degradation, leukocyte infiltration and angiogenesis. Many proteins have been observed to be highly up-regulated in both IBD tissue and CRC. Possibly one of the most important proteins to be highlighted are the cyclo-oxygenase (COX) enzymes, in particular COX-2. This inducible enzyme is over expressed in 90% of CRC (42). The induction of expression is seen early in acute inflammation, and high expression levels have been shown to be present in UC and CD. COX-2 produces a prostaglandin (PG) precursor (a member of the eicosanoid family of lipid mediators), with the main PG in the intestine being PGE_2. Accordingly, the membrane receptor for PGE_2 along with this PG are also over-expressed in IBD and CRC (43).

A further example linking CRC and IBD include, the observation that p53 mutations which are very common in CRC have been found in the inflamed mucosa from UC patients who did not have cancer. Also, methylation is a way of controlling gene transcription, with many proto-oncogenes being methylated in CRC. Several genes that precede dysplasia have been found methylated in UC (32,41).

Reactive oxygen species (ROS) and nitrogen oxygen species (NOS) are highly reactive molecules that are increased in the inflamed mucosa and remain elevated in colonic neoplasms (Fig. 3). ROS and NOS have also been

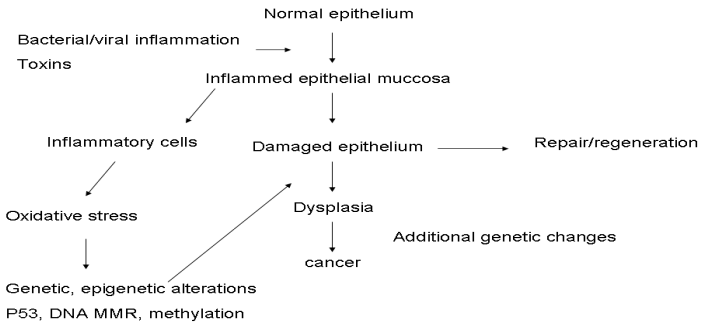

Figure3. Cascade of colitis associated CRC

implicated in the activation of Nuclear Factor κ B (NFκB) (44). NFκB is a significant player in inflammation. This family of transcription factors are known to be highly activated in many chronic inflammatory diseases and cancers, and have been proposed as one of the transforming factors between IBD and CRC (45). NFκB is a key regulator in inflammation and is also present in many solid tumours. It contributes to tumour formation by providing anti-apoptotic and survival signals to the epithelial cell. One way of triggering NFκB induced survival pathway in the GI tract is through the commensal bacteria (41). The commensal bacteria activate the appropriate TLR which in turn can activate NFκB, which can then affect the genes involved in survival. Under normal conditions this pathway is protective against colitis induced damage by blocking inflammation against commensal bacteria. However if the epithelial barrier is damaged these inflammatory signals reach the underlying inflammatory cells that can not distinguish between commensal bacteria and pathogens. This would then lead to a continuous inflammatory response to the commensal bacteria and an over stimulation of the survival signals leading to transformation (46). Another way of colitis induced transformation via this pathway might be when an insult or injury leads to mutate epithelial cells. These cells would then multiply due to the survival signals and lead to neoplasia. NFκB has been shown to stimulate NO and COX-2 to generate pro-inflammatory prostanoids that in turn can give

rise to carcinogenic effects. Active NFκB has also been found in inflamed mucosa in IBD. A known upstream effector of NFκB is the pro-inflammatory Tumour Necrosis Factor α (TNF-α). Antibodies against TNF-α are currently in the treatment of CD and UC. On the other hand PPAR-γ inhibits NFκB and is effective in reducing inflammation in CD (7,9). Impaired expression of PPAR-γ has been demonstrated in colonic epithelial cells in CD.

As previously mentioned the eicosanoids and the enzymes that produce them have been implicated in inflammation and CRC (39,47). Another enzyme 5-lipoxygenase (5-LO) produces other eicosanoids, the products, the cysteinyl leukotrienes (CysLTs) are the basis for the investigation presented in this thesis.

Highlighted signalling molecules

5. Phospholipase A_2

The phospholipases are a group of enzymes that catalyze the hydrolysis of the sn-2 ester bond in phospholipids (48,49). The outcome of this is the release of fatty acids and lysophospholipids (48,49).

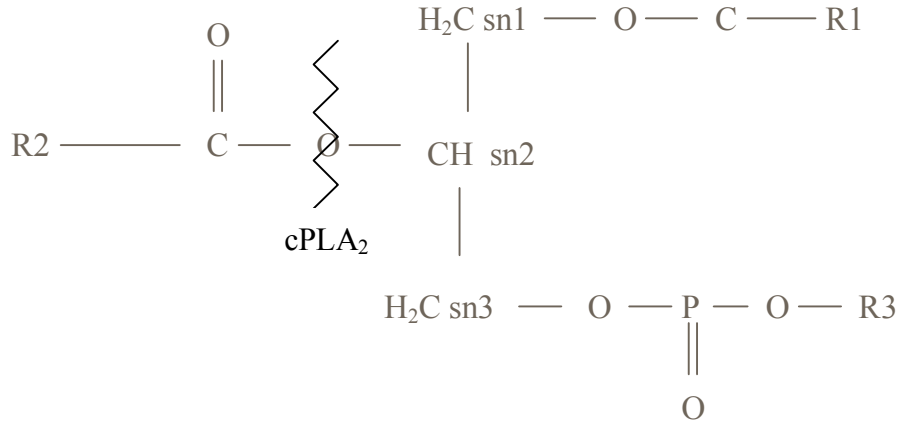

Figure4. cleavage site Sn-2 position of phsopholids.

When the fatty acid, AA is released, it can be further metabolised into a variety of bioactive lipid mediators termed the eicosanoids (50). The

eicosanoids (discussed below) are a family of potent mediators involved in many different conditions, such as inflammation and cancer (47,51,52). The lysophospholipids can in turn be converted into lysophosphatidic acid platelet activating factor (PAF) which also is a potent signalling molecule implicated in for example inflammation (53,54).There are currently 15 known groups and subgroups of Phospholipase A_2s (PLA_2) (55-57). These groups are separated by characteristics of the PLA_2s such as their; structure, requirement for calcium and size. This divides the PLA_2s in to five major groups; the $sPLA_2$s (secreted), the $cPLA_2$s (cytosolic), the $iPLA_2$s (calcium independent), the PAF acetyl hydrolases and the lysosomal PLA_2s. The $sPLA_2$ group have a low molecular weight (14-19kDa) and are calcium dependent (55,56). The different members of the $sPLA_2$ family have been implicated in the digestion of phospholipids in the stomach (58,59), rheumatoid arthritis (60), hydrolyzing membranes of gram negative bacteria (anti-microbal agents) (61,62), atherosclerosis and IBD (63-65). It has also been demonstrated to decrease the size and development of tumours in mice. Increased expression in mice, has been correlated with a better survival, however this data contradicts the results detected in humans, where the enzyme is up-regulated and may be contributing to the progression of CRC (66). The exact role of $sPLA_2$ in eicosanoid production remains unexplained, but might depend on cell type and stimuli.

The $iPLA_2$ group have molecular weights ranging from 28-146 kDa. Whilst they do not have fatty acid chain specificity, they are thought of as house keeping genes but also been shown to be involved in apoptosis by delaying or inhibiting cell death induced by death receptors (55).

The PAF acetylhydrolase group (also shown to be anti-inflammatory) do not require calcium for their activity, they range from 26-45 kDa, and some are secreted and some are intracellular but they all hydrolyse the acetyl group from the sn-2 position of PAF (67-69). The PAF acetylhydrolase IIA is secreted and can also hydrolyse short fatty acids from the sn-2 position, it can

bind to both the high density lipoprotein and low density lipoprotein cholesterol molecules (69,70) and not surprisingly has been implicated in cardiovascular disease (71). Lysosomal PLA_2 is the most recently discovered being found in bovine brain and does not require calcium for its activity (72).

The $cPLA_2$s are serine esterases, they have a molecular weight of 61-114 kDa, and all but cPLA2-γ/IVC require calcium. The different $cPLA_2$s have different specificities for fatty acids in the sn-2 position with cPL_A2-α/IVA being specific for AA containing phospholipids whilst $cPLA_2$-β and γ have very little specificity for AA (73,74). A major role of cPLA-α is in the production of eicosanoids. cPLA2-α is an 85kDa enzyme, isolated from neutrophils and platelets (75,76). It is composed of a C2 calcium binding domain, that is required for its membrane translocation, α and β -hydrolase domains with the catalytic site, and the serine 727 and 505 that are phosphorylated by the Mitogen Activated Protein Kinases (MAPK) and MAPK activated proteins. The phosphorylation of the $cPLA_2$s is important for the lipid enzyme interaction. (55,77). Even though $cPLA_2$-α requires calcium for its translocation and membrane binding, phosphoinositol diphosphate (PIP2) has been shown to activate the protein in a calcium independent manner. The PIP2 binding domain is in the catalytic site but has been shown to require the C2 domain (78). The importance of this protein in inflammation has been demonstrated in knock-out mice, which have post-ischemic injury, acute lung injury and significantly decreased allergic responses. Furthermore, the first study in this thesis demonstrates that the pro-inflammatory mediator leukotriene D_4 (LTD_4) can activate and increase expression of $cPLA_2$-α (79).

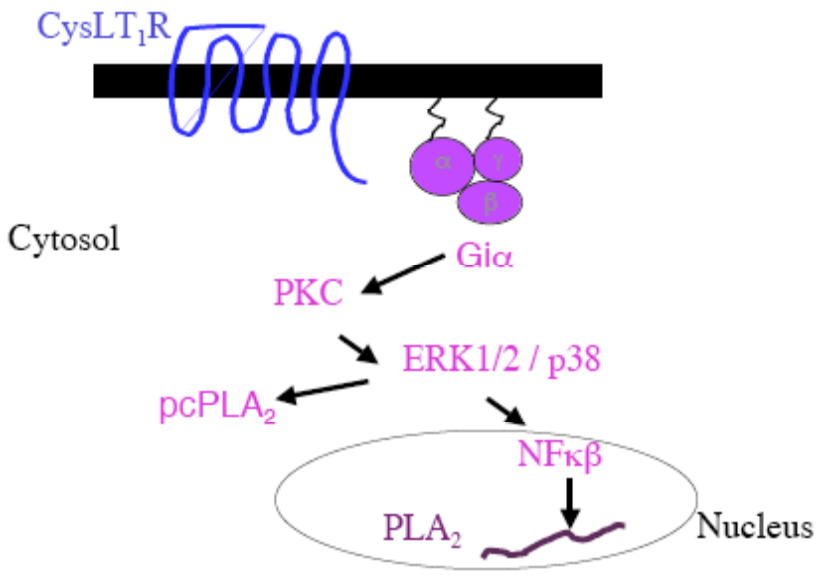

Figure5. LTD4 mediated cPLA$_2$α activation and transcription.

A variety of mediators have been shown to activate cPLA$_2$ such as; cytokines, chemokines, growth factors, histamine and thrombin. The promoter region of cPLA$_2$ has been shown to contain potential binding sites for amongst others NFκB, AP1 and AP-2 (73,80). Over-expression of cPLA$_2$-α has been demonstrated in a variety of cancers such as cholangiocarcinoma and non small lung squamous carcinoma (81-83). The expression and activity of cPLA$_2$-α in CRC however is a more complicated affair. Early studies of the expression and activation of cPLA$_2$ in colon tumours demonstrated elevated expression and function compared to non-transformed material (84). Another group demonstrated similar results using primary CRCs. In the study in this thesis, cPLA$_2$ levels were increased in colon cancer cells compared to non-transformed cells from the small intestine. Tumour samples were also examined, and elevated levels of cPLA$_2$-α were detected as compared to non-transformed tissue. Another group has also reported that cPLA$_2$-α and COX-2 were elevated in colorectal adenocarcinomas (85). Here over-expression of cPLA2-α was found in superficial stromal cells and correlated with an

increased COX-2 expression and high micro vessel density (85), suggesting a regulatory role for $cPLA_2$-α in COX-2 induced angiogenesis. This group analysed another set of CRC specimens and found elevated levels of cPLA2-α, but could not correlate them to any specific stage, histological pattern or microsatelite instability (86). They could however, yet again show a correlation between $cPLA_2$-α and COX-2 in half of the samples (86). A mouse model using APC min mice produced conflicting results concerning $cPLA_2$-α in colon cancer (87). This group found a decrease in the expression of $cPLA_2$-α in five human colorectal cancers. The same study also reported that despite low levels of $cPLA_2$-α, COX-2 expression was elevated. These studies were further explored (88) and 13/27 samples showed elevation of COX-2 and in 11 of these 13 samples $cPLA_2$-α was reported absent. The authors suggest that the low levels of $cPLA_2$-α and high levels of COX-2, probably disrupts the levels of AA (high levels of AA induces apoptosis) leading to escape from apoptosis. In another study by the same group, AOM induced colon cancer, was investigated in $cPLA_2$-α knockout mice, which showed increased tumour size and number in the colon (89). The authors also observed enhanced tumorogenesis despite low levels of COX-2 in their model (89). Further APC min mouse studies have shown that in the small intestine, $cPLA_2$ is the dominant source of AA for COX-2 (90) and that deletion of $cPLA_2$ reduces tumour size and/or number even in the colon (90-92). The conflicting results can also be seen in the regulation of $cPLA_2$-α by AA metabolites. In a study using prostate cancer cells (PC-3), AA was added directly to the cells. This lead to a transcriptional activation of $cPLA_2$-α and COX-2 in a dose dependent manner, and an increase of PGE_2 production. Interestingly the authors show that a COX-2 inhibitor blocked the up-regulation of $cPLA_2$-α and COX-2, suggesting that PGE_2 can up-regulate $cPLA_2$-α (100). Again there is a contradictory study preformed in mouse lung fibroblasts, where the addition of PGs could only up- regulate COX-2 but not $cPLA_2$-α (101). These data suggest that the regulation of $cPLA_2$-α to some extent might be tissue specific.

Surprisingly, a very recent study reported the findings of $cPLA_2$-α deficiency in a 45 year old white American male of Italian decent. The study showed that this man suffered from multiple ulcers in the small intestine and concluded that $cPLA_2$-α plays an important role in intestinal homeostasis and integrity. Furthermore he had platelet dysfunction and globally decreased eicosanoid production. The findings suggest that the production of eicosanoids in platelet and leukocytes is almost entirely dependent on $cPLA_2$-α. However, the study also showed that the outcome of several colonoscopies preformed, were normal despite the absence of $cPLA_2$-α. Moreover, the authors reported that their results indicate that $cPLA_2$-α provides AA for virtually all biosynthesis of eicosanoids by platelets, leukocytes and the cells from which the CysLTs are derived (93).

6. Eicosanoid

The eicosanoids are biologically active fatty acid metabolites with a twenty carbon chain backbone (94). Their name originates from the Greek word eicosa, which means twenty. Eicosanoid is the umbrella term for metabolites of AA. AA is found in membrane phospholipid bilayers. Once released by PLA_2, AA can be further metabolized by the COXs, LOs, cytochrome p450 or non-enzymatically. When oxygenated by COX, AA gives rise to PGs, prostacyclin or thromboxanes. Oxygenation by LOs gives rise to LTs, lipoxins, hepoxillins or monohydroxy fatty acids (49,95-98). Cytochrome p450 metabolism of AA forms epoxy fatty acids or dihydroxy fatty acids. Non-enzymatic metabolism of AA produces isoprotnes or isoleaukotrienes(99-101).

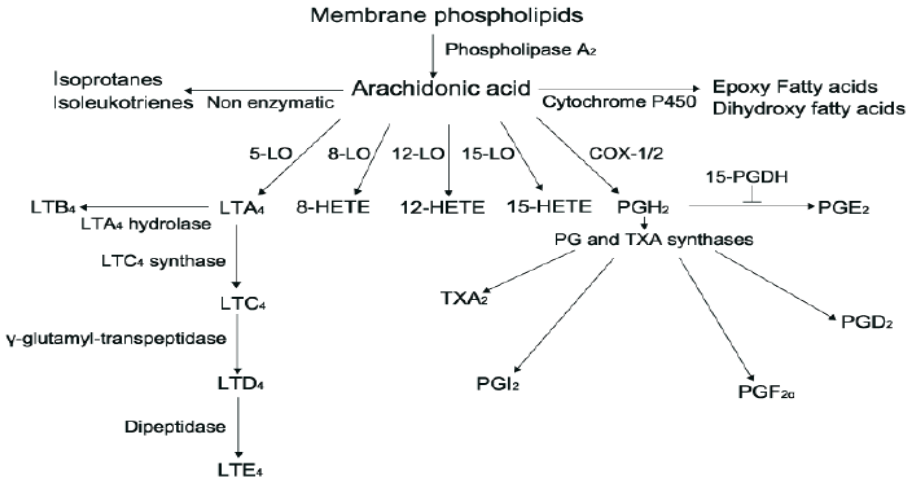

Figure6. Eicosanoid production.

Cyclooxygenases and Prostaglandins

The COX enzymes initiate the synthesis of PGs, and can be divided into two established isoforms; COX-1 and COX-2. The enzymes share a 60% homology (95,102,103) and consist of three domains; an EGF domain, a membrane binding domain and a catalytic domain that controls both its COX and peroxidase activity (104). COX-1 is a house keeping enzyme and produces basal levels of PGs. COX-1 is ubiquitously expressed and needed for homeostasis, for example in maintaining the epithelial barrier (105,106). It should however be mentioned that COX-1 has been shown to play a role in ovarian cancer (107). COX-2 is an inducible enzyme and its expression can be mediated by many inflammatory mediators (108). It has also been shown to be over-expressed in IBD, CRC (90%) and many cancers. Inhibitors of the COXs have been used for over a 100 years (109-111). Non-steroidal anti-inflammatory drugs (NSAIDs; aspirin, indometacin, and ibuprofen) block both COX-1 and COX-2. Specific COX-2 inhibitors have been shown to reduce tumour size and colonic polyps (42). These positive effects are however

clouded by the cardiovascular side effects which were seen with a particular COX-2 specific inhibitor in a subset of patients being treated for Rheumatoid arthritis, leading to it being pulled from the market (105). However, other COX-2 specific inhibitors are still used in treating inflammatory conditions although with greater caution (112,113). With this in mind, there is also data demonstrating that COX-2 also is involved in anti-inflammatory and pro-resolution pathways, and perhaps COX-2 inhibitors are not optimal in this regard either (104,114). AA is metabolized by COXs to the PG precursor PGH_2. PGH_2 is then further metabolized to PGI_2, PGE_2, PGD_2 or $PGF_2\alpha$ via specific PG synthases (42). The PGs were discovered in 1935 and have since then been implicated in various signalling pathways (115). Similarly to COX-2, PGE_2 has been implicated in IBD and CRC. PGE_2 has been shown to increase cell survival, proliferation and migration and be directly involved in angiogenesis (116-118). The effects of PGs are exerted through G-protein coupled receptors termed EP1-4. These receptors have been shown to be expressed at the plasma membrane as well as the nuclear membrane (118-120).

Leukotrienes

The leukotrienes (LTs) are named after their structure and the cells that they were discovered in. Leuko means from white blood cells and trienes stands for the three double bonds in their structure (121). They are inflammatory mediators derived from AA through the action of 5-LO (121). AA is a 20-carbon polyunsaturated fatty acid derived from food or from the conversion of the essential fatty acid linoleic acid (94). It is usually found esterified in the membrane phospholipids and is released by PLA_2 (94). Glucorticosteroids, common treatments for inflammatory conditions, act by inhibiting the transcription of PLA_2 (122). 5-LO which belongs to a family of LOs comprising of 5-, 8-, 12- and 15-LO (123,124) is responsible for initial step in the production of the LTs converting AA to LTA_4.

The unstable LTA_4 produced by 5-LO is rapidly converted to LTB_4 or the CysLTs; LTC_4, LTD_4 and LTE_4 (52,125,126). All LTs exert their effects through G-protein Coupled Receptors (GPCRs). The CysLT receptors are termed $CysLT_1$, $CysLT_2$, $CysLTE_4$ and GPR17 (127,128) and have been shown to be involved in various inflammatory conditions such as asthma, IBD, cancer, and arthrosclerosis (129). The CysLTs are produced upon immune and inflammatory stimuli (50,130).

LTD_4 has been shown to induce cell proliferation, survival (131,132) and cell migration (133), as well as up-regulating several anti-apoptotic and survival proteins such as BCL-2, β-catenin(134) and COX-2, in intestinal epithelial cells.(135). LTD_4 induces proliferation in epithelial cells via two distinct pathways. One pathway is mediated by Protein Kinase C (PKC) -ε, MEK1/2 and ERK1/2 leading to p90RSK activation; the other pathway is mediated through PKC-α and CREB (131,132). Furthermore LTD_4 is this thesis has been shown to induce cell proliferation through $cPLA_2$-α (79). The same study also shows that the activation of $cPLA_2$-α is mediated through $CysLT_1R$, a pertussis toxin (PTX) sensitive G-protein, PKC, p38, ERK1/2 and calcium. Correspondingly, in renal messengial cells, LTD_4 induced proliferation requires activation of ERK1/2, p38, phosphatidyl inositol 3-kinase (PI3-K) and PKC (136) and in mast cells, LTD_4 also induces proliferation (137). In addition to $cPLA_2$-α activation, LTD_4 is shown to the induce expression of $cPLA_2$-α in a similar fashion to the proliferation, which suggested a role for NFκB. In another study LTD_4 induced $CysLT_1R$ signalling in HEK293 cells stably expressing $CysLT_1$ lead to IL-8 expression in a NFκB and AP1 dependent manner (138). Recent data from our group also confirmed the short term activation of NFκB by LTD_4 (unpublished data), although long term stimulation with LTD_4 does not seem to activate NFκB (139). Interestingly, in contrast to LTD_4 induction of proliferation, LTC_4 has been demonstrated to promote differentiation in CRC cells (140) and have a chemotactic effect (141).

In addition to the cellular effects named above, the LTs also affect several other cells for example, LTB_4 is a chemoattractant as well as being involved in promoting adhesion and rolling of leukocytes. The actions of LTB_4 are distinct from those of the CysLTs. LTB_4 recruits mainly leukocytes to the site of inflammation and subsequently triggers their degranulation (142,143). The CysLTs are also chemoattractants but mainly for eosinophils and induce leakage and mucus secretion (144,145). They are also known to be potent inducers of smooth muscle contraction that is involved in bronchi constriction and have been shown to be 10,000 times more potent than histamine (146). Due to this, several drugs directed against the effect of the CysLTs have been developed (144,145).

The LTs are predominantly produced in blood cells as suggested by the name, but can be synthesized by other cells, lacking the whole biosynthetic machinery required, through transcellular biosynthesis (147). An example of this is the interaction of endothelial cells and neutrophils. Neutrophils produce LTA_4 and secrete it. Endothelial cells which lack sufficient amounts of 5-LO but express LTC_4 synthase then take up the LTA_4 and convert it to LTC_4 (147).

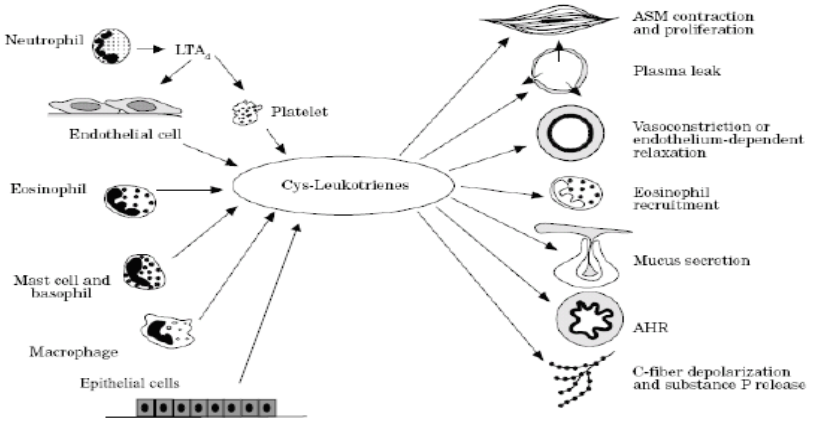

Figure7. Cells producing leukotrienes and the effects of leukotrienes. Modified from Nicosia et al. ,2001

In epithelial cells, LTD_4 can induce the production of CysLTs in an autocrine fashion (148) as wells as inducing production of PGs via COX-2 induction (149). The cell death induced by COX-2 inhibitors in intestinal epithelial cells could be escaped by the cells through LTD_4 stimulation (150). LTD_4 has also been shown to induce a rapid calcium response in intestinal epithelial cells as well as CRC cells (151,152). This calcium response has been demonstrated to be mediated through a PTX sensitive G-protein, leading to cAMP release and PKA activation (153,154). In resting cells 5-LO is located in the cytoplasm but when activated it translocates to the nuclear membrane, and with the help of Five Lipoxygenase Activating Protein (FLAP) converts the released AA to LTA_4 (155).

7. Cysteinyl leukotriene receptors

The LT receptors are GPCRs that were cloned and characterised late in the 1990's (156-160). The first receptor to be cloned was the first LTB_4 receptor, BLT_1R (161) and only three years later a second LTB_4 receptor; the BLT_2R was cloned (162). BLT_1 is the high affinity receptor for LTB_4 and BLT_2 is the low affinity receptor. The CysLTs have so far been shown to exert their effects mainly through two receptors; the $CysLT_1R$ and $CysLT_2R$ (156-160). However, recent discoveries reveal the existence of two new receptors; the orphan receptor GPR17 (163) which has higher affinity for LTC_4 than LTD_4 and a potential $CysLTE_4R$ (127) with a high affinity for LTE_4. GPR17 has also been shown to bind uracil nucleotides (124). The CysLTs bind $CysLT_1R$ with the following different affinities; $LTD_4<LTC_4<LTE_4$. LTD_4 binds $CysLT_1R$ with the highest affinity (EC50 = 0.4nM) whilst LTC_4 binds $CysLT_1R$ with a 350 times lower affinity (EC50 = 21nM). LTE_4 is a less potent agonist and has been shown to sometimes act as a partial agonist (130,159,160,164). LTD_4 and LTC_4 have equal affinity for $CysLT_2R$ and LTE_4 has an even lower affinity (158).

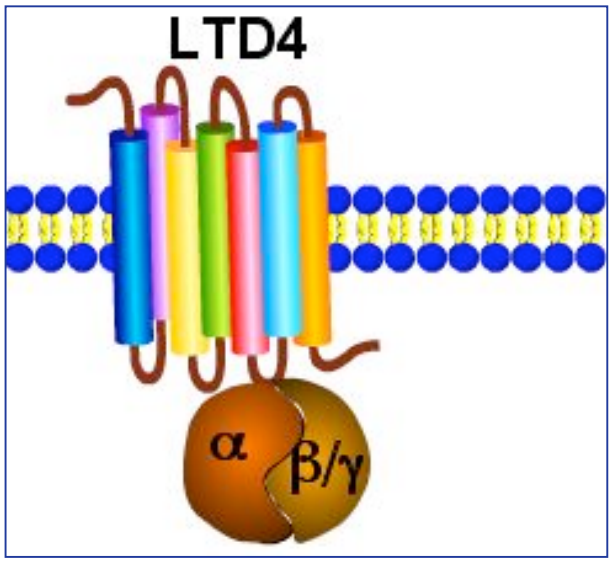

Figure8. The Cysteinyl leukotriene receptor 1.

The $CysLT_1R$ is encoded on the X chromosomes while the $CysLT_2R$ is encoded by chromosome 13 and the two receptors share a mere 38% homology. Both receptors were cloned almost at the same time in 1999. $CysLT_1R$ has a molecular mass of 38 kDa in its monomeric form (159,160) yet is often detected oligomerized (165). The $CysLT_1R$ has four potential N-glycosylation sites and many potential PKC and PKA phosphorylation sites in its third intracellular loop and C-terminus (160). It is known to be involved in various signalling pathways and cellular functions such as; MAPK activation, calcium increases, actin reorganization, proliferation, survival, differentiation, and migration (79,166,167). In the last 20 years, an array of various inhibitors targetting the $CysLT_1R$, have been developed. Montelukast, Zafirlukast, Pranlukast (IC50 = 1.8–4.9nM) are some of the examples of inhibitors for the $CysLT_1R$ (159).

The $CysLT_2R$ is a protein of 346 amino acids and migrates at 49-58 kDa (168). It also contains 4 N-glycolysation sites mainly in its N-terminus and PKC and PKA phosphorylation sites in its third internal loop and C terminal tail (158). Binding studies in Cos-7 cells with this receptor reveal the presence of two binding sites, one low and one high for LTD_4. In another study the affinity for LTC_4 for $CysLT_2R$ was detected in the nano molar range (156-158) whilst all of the $CysLT_1R$ selective antagonists were demonstrated to be

inactive in a competition assay. Bay u9773 which has been suggested as a $CysLT_2R$ antagonist but was later shown to also be a partial agonist of both receptors (156,158). HEK-293 cells transfected with the $CysLT_2R$ also demonstrated that LTC_4 and LTD_4 are equipotent agonists but that LTE_4 is a partial agonist (156-158).

The distribution of $CysLT_1R$ and $CysLT_2R$ receptors is mostly overlapping but high expression of $CysLT_2R$ has been detected in heart, brain and the adrenal glands (128,156-158). Intestinal epithelial and CRC cells express both receptors (140,169,170) and the expression of each receptor in CRC cells varies, although in general $CysLT_2R$ seems to be down regulated in CRC patient material whilst $CysLT_1R$ seems to be up-regulated in comparison to the surrounding non-transformed tissue (140,169,171).

The recently discovered GPR17 has been shown to have a higher affinity for LTC_4 than LTD_4 (163). The idea that additional receptors may exist came from a few unexplainable data such as: LTC_4 or LTE_4 failing to activate $CysLT_1R$ or $CysLT_2R$ and also from the fact that the response from LTC_4 was more potent than that of LTD_4, which does not fit with the affinity studies preformed on the $CysLT_1R$ and $CysLT_2R$ (172-175). In 2001 a report described that $CysLT_1R$ and another yet unidentified receptor, although not the $CysLT_2R$, both responded to uracil nucleotides and CysLTs. Later another study investigated the orphan receptor GPR17 and found that it responds to both CysLTs and extracellular nucleotides (163). Interestingly two $CysLT_1R$ inhibitors (pranlukast and montelukast) could block the LTD_4 induced response of GPR17 and as could two antagonists of the P2YR family (163). GPR17 binds the CysLTs in the nano molar range whilst the potency range for the extracellular nucleotides is in the micro molar range (UDP-galactose = UDP > UDP-glucose). All the responses from GPR17 have been demonstrated to be PTX sensitive and both types of agonists induce a calcium response and inhibition of forskolin induced cAMP formation. GPR17 is highly expressed in tissue undergoing ischemic injury such as heart, brain and kidney

suggesting its involvement in these conditions. Infact knock-down or inhibition of GPR17 by either CysLT1R or P2YR antagonists protects against brain damage (163). A recent study preformed in $CysLT_1R$ / $CysLT_2R$ knockout mice showed a LTE_4 induced vascular permeability response. This led the authors to hypothesize that yet another CysLT receptor existed with high affinity for LTE_4. The authors continued by showing that in mice lacking $CysLT_1R$ and $CysLT_2R$, LTC_4 and LTD_4 could induce vascular leak but to a lesser extent than LTE_4. The effect of LTE_4 was 64-fold greater in deficient mice than the wild type mice. The response from all three ligands in double deficient mice could be blocked by pranlukast, a $CysLT_1R$ inhibitor. The authors concluded from this data the existence of a new CysLT receptor, termed $CysLTE_4R$ (127).

$CysLT_1R$ internalisation has been studied in Cos-7 cells transfected with the receptor and stimulated with LTD_4. In this study $CysLT_1R$ was internalised in a PKC dependent manner, where PKC phosphorylated the $CysLT_1R$ in the C-terminus, and that lack of this phosphorylation impaired receptor internalisation. Furthermore, the same study identified that the internalisation of $CysLT_1R$ is β-arrestin independent (176). In contrast to this, a separate study preformed in U937 human macrophage like cells, also transfected with $CysLT_1R$ provided evidence that the LTD_4 induced desensitization of $CysLT_1R$ is not PKC dependent but GRK2 dependent. However, the PKC phosphorylation of $CysLT_1R$ was shown to be important in the extracellular nucleotide induced $CysLT_1R$ desensitisation, although this does not lead to its internalisation, rather it shows a rapid recovery of the receptor (165). Data from the second project in this thesis demonstrates a clathrin, EPS15, β-arrestin-2, Rab5 mediated internalisation of $CysLT_1R$ upon LTD_4 stimulation.

Various signalling pathways have been established for $CysLT_1R$ in a variety of cells and tissues. The signalling of $CysLT_2R$ has been less clarified due to the lack of specific inhibitors. Contrasting reports regarding the expression and signalling of $CysLT_1$ and $CysLT_2$ in HUVEC cells have been

reported. Some reports have identified the expression of $CysLT_1R$ in these cells coupled with a calcium response from both LTD_4 and LTC_4 in these cells that can be blocked by Pobilukast. Other groups have stated that these cells mainly express the $CysLT_2R$ and have shown that this expression is highly up regulated by IL-4 and also that $CysLT_2R$ is responsible for the calcium signals exerted by LTD_4, LTC_4 and Bay u9773 (177-179). Additionally, LTD_4 induced $CysLT_2R$ activation in HUVEC cells has been shown to up-regulate 37 early inducible genes, which included for example early growth response (EGR) and COX-2 (180). In a study with mast cells the authors use MK 571, a selective $CysLT_1R$ inhibitor, and show that the IL-8 production by the IL-4 primed and CysLT or UDP stimulated cells was not inhibited, but that Bay u9773 was able to evoke IL-8 production. Interestingly, they show that inhibition of p38 blocked the IL-8 production, suggesting a role for p38 downstream of $CysLT_2R$ (181). Studies in human coronary artery stimulated with LTC_4 show a calcium response which is unable to be blocked by $CysLT_1R$ antagonists (141). In oxygen/glucose deprived PC12 cells, cell death was shown to may be mediated by $CysLT_2R$ since Bay u9773 inhibited this effect and $CysLT_1R$ seemed to reduce cell death (182).

A novel mechanism for receptor regulation was described for $CysLT_2R$, which has been suggested to negatively regulate the plasma membrane expression and signalling of $CysLT_1R$ in mast cells. Moreover the authors gave evidence for dimerization of $CysLT_1R$ and $CysLT_2R$ (183). Studies preformed by J.A Boyce and co-workers recently reported by Rovati et. al, suggest $CysLT_1R$/ $CysLT_2R$ dimers at the nuclear membrane of mast cells (128).

Our group have published data indicating the existence of both receptors at the nuclear envelope in intestinal epithelial cells and CRC cells (140,169). Furthermore, $CysLT_1R$ can localise to the outer nuclear membrane and translocate from the plasma membrane to the nuclear membrane upon stimulation with LTD_4 (169). The COX-2 gene up-regulation mediated by

LTD_4 requires the internalisation of the receptor and we hypothesise that this signal is mediated through the translocation of $CysLT_1R$ to the nuclear membrane. In contrast to COX-2, Cyclin D1 mRNA up-regulation and the LTD_4 induced ERK1/2 phosphorylation are increased when receptor internalisation is blocked. This leads us to hypothesise that the plasma membrane $CysLT_1R$ can continue to signal and respond to LTD_4 when its internalisation is blocked and can therefore increase the signals mediated from the plasma membrane.

8. Mitogen activated protein kinases

Mitogen activated protein kinases (MAPKs) are serine threonine kinases involved in a variety of signalling cascades mediating cellular responses such as proliferation, apoptosis, differentiation and survival. MAPKs need to be phosphorylated for full activation and the pathways they regulate are sometimes cross linked or dependent on each other (184). In contrast, MAPKs are negatively regulated by de-phosphorylation. There are seven families of MAPKs and they can be dived in the classical MAPKs (ERK1/2, p38, JNK and ERK5) and the atypical MAPKs (ERK3, 4, 7 and NLK) (185,186). Phosphorylation of MAPKs occurs in their catalytic loop and these phosphorylations are regulated by upstream MEKS/MAPKK. MEKs in turn are regulated by MAPKKK, such as Raf. In summary different stimuli activate MAPKKK that in turn activate MAPKK and MAPKs (187). Raf can be activated by a family of small monomeric GTPases such as Ras. Ras has been shown to be mutated in 30% of all cancers and B-Raf is mutated in 60% of all malignant melanomas (188).A classical pathway is that of mitogens or growth factors activating PKC which in turn can lead to the activation of Ras and Raf. Raf then activates MEK1,2 which phosphorylate and activate ERK1/2. ERK1/2 activation leads to the activation of various transcription factors such as NFκB, inducing cell survival and proliferation (186,189-192). The p38 MAPK family consists of four isoforms; α, β, γ and ε (189). They are activated

by stress and inflammatory cytokines. Most stimuli that activate p38 can also activate JNK. MEK6 can activate all p38 isoforms whilst MEK3 activates α and β (193). p38 has been shown to be critical for normal immune and inflammatory responses (194). Mitogens or growth factors can also activate (via MEK1-4 or MEK3, 6) the p38 MAPK which has been shown to be involved in differentiation, apoptosis but also cell growth and survival. Downstream targets of p38 include p53 and NFκB (45,195,196). Both p38 and ERK1/2 have been implicated in IBD. ERK1/2 has been demonstrated to be over expressed and also overly active in IBD (186). Many cytokines can activate ERK1/2 such as IL-21 and IL-1(186,189). p38 and JNK families have however been the centre of investigation concerning MAPKs and IBD (197,198). Inhibition of p38 and JNK have been shown to reduce cytokine production (199).

9. NF-κB

The NF-κB family are transcription factors involved in many inflammatory pathways. They have been suggested to play a major role in IBD and CRC (41,45). Epithelial cells isolated from IBD patients show increased expression of NFκB. Furthermore, constitutively active NFκB has been found in human cancer cell lines as well as in tumours from patients suffering from CRC, breast cancer, leukemia and prostate cancer. Suppression of NFκB in these tumour samples inhibits proliferation, causes cell cycle arrest and leads to apoptosis (200). Many cytokines and growth factors such as TNF-α or EGF mediate their proliferative effects through activation of NFκB. It has been suggested that NFκB is one of the major links between inflammation and cancer (200). This family consists of five members, p50, p52, p65 (RelA), c-

Rel and RelB, which share an N-terminal Rel homology domain (RHD) responsible for DNA binding, nuclear targeting and homo and heterodimerisation. NF-κB dimers bind to various pro-inflammatory, anti-apoptotic and cell cycle regulating genes. It is however only the p65, c-Rel and RelB that are able to directly activate transcription of target genes. P50 and p52 need to dimerize with p65, c-Rel and RelB, for gene activation whilst homo-dimerization of p50 and p52 can suppress transcription. NFκB was first discovered in inflammatory cells but has since been shown to be expressed in various cell types (45,200,201). When activated NFκB translocates to the nucleus, whilst in its inactive state NF-κB dimers are bound to specific inhibitory proteins IkBs, in the cytoplasm. The IκBs can be divided in to IKB-α, β and γ. They keep NF-κB in its inactive state by masking its nuclear localization sequence. IκB-α has also been shown to translocate to the nucleus, inhibit NFκB from binding to its target genes and export NFκB out of the nucleus. However upon stimuli, the IκBs are phosphorylated, ubiquitinated and sent for degradation. This then release NFκB to translocate to the nucleus and bind to its target genes (201). The activation of NFκB can be divided in to the classical and the alternative pathways. The classical pathway can be activated by for example pro-inflammatory cytokines such as TNF-α or IL-1, bacterial LPS and viruses. These signals lead to activation of IKK (IKB kinase complex) which is composed of IKK-α and β as well as the regulatory NEMO. The catalytic subunits (IKK α and β) phosphorylate serine residues in the IKB proteins. In the classical pathway this phosphorylation is mediated mainly through the IKK-β and results in IκB being sent for degradation and NFκB translocating to the nucleus. In the alternative pathway, IKK-α is predominant in the activation process. In this pathway p100, the precursor of p52, is cleaved into p52, which then translocates to the nucleus (202-204). NEMO is not absolutely required for the alternative pathway. Some of the inducers of the classical pathway can also induce the alternative pathway, such as TNF-receptor family member CD40. Other NFκB activators are the Nod proteins (1

and 2) which are cytoplasmic receptors for microbial ligands, or the TLR that via TRAF6 and MEK1/3 can activate the IKK complex. MEK 1,3 can activate and regulate both ERK1/2 and p38, both of which have been shown to be involved in activation of cPLA2-α and proliferation of intestinal epithelial cells (201).

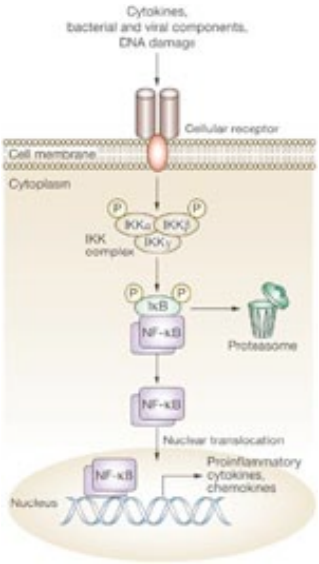

Figure9. Classical and atypical activating pathways of NFκB.
http://www.biomedcentral.com/nspprimers/nfkb/full

10. Protein kinase C

The protein kinase C (PKC) family consists of 10 mammalian isoforms divided into three groups; the classical, novel and the atypical. The classical PKCs include the α, βI, βII, and γ PKCs. These isoforms need calcium, diacylglycerol (DAG) and phosphatidyl serine (PS) for activation. The novel PKCs consist of PKC*δ*, PKCε, PKC*η*, PKC*μ*, PKC*θ*, and do not require calcium but do require DAG and PS for activation. The atypical PKCs (PKC*ζ*, PKC*ι*/*λ*) only require PS for activation (187,205). PKCs are activated by phosphorylation and binding of PKCs to the cytoplasmic side of the plasma membrane. The membrane targeting domains are the C1 domain which binds DAG and C2 which binds acidic lipids. PKCs are serine threonine kinases and

consist of a regulatory N-terminal that binds calcium, co-factors and lipids (C1 and C2). When co-factors bind these domains they release a pseudo substrate that otherwise blocks the activation site of PKCs. They also have a catalytic C-terminal that is an ATP substrate binding domain (206). PKCs are involved in many different pathways and signalling cascades by phosphorylating many different proteins. Three types of amino acids are known to be phosphorylated; serines, threonines and tyrosines. When PKC phosphorylates other proteins in their serine or threonine site, it changes the state of these downstream proteins and activates or allows them to bind to other proteins. GPCRs, tyrosine kinase receptors, ion channels, and transcription factors and enzymes such as PLA_2s are just some of the types of proteins that are phosphorylated by PKCs (207). In the case of GPCRs PKC has been shown to phosphorylate them once they have been activated by their ligand. This phosphorylation then can desensitize and/or help the GPCR associate with the endocytic machinery (207). Two ways of inhibiting PKCs include the use of calphostin C which competes with DAG/PS and inhibits the membrane translocation of PKC. The other way is used by GFX and Gö inhibitors which inhibit the catalytic activity of PKC by competing with ATP (208,209). We have previously shown several PKC members to be important in LTD_4 mediated signalling. PKCδ was shown to be important for stress fibre production induced by LTD_4 (210), whilst interestingly two PKCs namely PKCα and ε, are involved in cell proliferation (132).

11. G-protein coupled receptor structure and signalling

G-protein coupled receptors (GPCRs) are a family of seven transmembrane spanning receptors that sense molecules outside of the cells and activate intracellular signal transduction pathways and cellular responses by coupling to heterotrimeric G-proteins (211).

GPCRs are one of the largest known families in the genome. There are approximately 865 potential GPCRs which equals about 3.5% of the human

genome set (212,213). Approximately 30%-45% of all patented drugs in current clinic use are GPCRs (213,214). GPCRs contain 7 hydrophobic stretches of 22-25 residues which are long enough to cross a membrane when folded (7 transmembrane domains) creating three external and three internal loops with an external N-terminal and a cytoplasmic C-terminus. The trans-membrane domains of GPCRs are highly conserved. The bovine rhodopsin GPCR has been crystallized and its structure has served as a template for other GPCRs (215) (216). The GPCRs have a variety of different ligands including; hormones, neurotransmitters, chemokines, calcium ions, sensory receptors for various odorants, tastes and photons of light. There are two broadly defined functional classes of GPCRs; The sensory receptor homologs and the non-sensory receptor homologs. In 2004 the Nobel prize went to Linda Buck and Richard Axel for demonstrating that odour precipitation results from several different GPCRs on different neurons (217). The GPCRs can further be classified into three families based on their sequence. The first family (Family1/A) has the closest structure to Rhodopsin and is the largest family. They have a short N and C terminus and include most of the olfactory receptors but also 200 of the non-olfactory receptors belong to this group (218). The second family (2/B) only has 25 members and they are characterised by their long N-terminus and the fact that they mainly activate cAMP through the G_s G-protein. This family includes the parathyroid hormone receptor, secretin receptor, adrenomedulin receptor and glucagon receptor (218). The third family (3/C) have long N and C terminals, mostly bind their ligands in the N-terminus and include the $GABA_bR$, calcium sensing receptors, some taste receptors and the orphan receptors, where the natural ligands are unknown (218).

GPCRs have been shown to exist in a conformation equilibrium between inactive and active state in the absence of ligand (219). The binding of ligands shifts the equilibrium either towards the active or inactive state. Three types of ligands exist; agonists which shift the equilibrium to active state, inverse

agonists which shift the state to inactive and also prefer to bind receptors in the inactive equilibrium state. The inverse agonists have been demonstrated to have the opposite effect of agonists. There are also neutral antagonists that bind the GPCR and lock it in an inactive state (220). As mentioned above this activation state can also be induced spontaneously without ligand as well as in receptors containing mutations that lead to constitutive activity which has been demonstrated in various pathological conditions (221). There are four different mutations known in the Rhodopsin receptor that causes it to be constitutively active that can lead to blindness (222). Mutations creating a constitutively α-1-β -adregenic receptor have been demonstrated to have mitogenic and tumorogenic effects (223).

Malignant cells or their surrounding stromal cells often abuse the functions of GPCRs to be able to proliferate, induce angiogenesis (growth, migration and blood supply) and survive apoptosis. This is often achieved by either expressing constitutively active GPCRs or more commonly by over-expressing particular GPCRs (224). Furthermore over-expression of constitutively active G-proteins have also been implicated in cancer, the most potent ones being G-$\alpha_{12/13}$ (225,226).

Heteromeric G-proteins are composed of the α, β and γ subunits. In their inactive state the α subunit of the G-protein is bound to guanine dinucleotide phosphate (GDP). Upon activation the GDP is exchanged for a guanine trinucleotide phosphate (GTP). This leads to the disassociation of the α subunit from the β and γ subunits. These subunits can stimulate several downstream pathways. The α subunit has an intrinsic ability to hydrolyse the GTP back to GDP. The G-proteins are classified according to their α subunit. The G-α_s stimulates cAMP production by stimulating adenylylcyclase whilst the G-α_i inhibits cAMP production. The G-$\alpha_{q/11}$ activate PLC which cleaves PIP2 to IP3 and DAG. G-$\alpha_{12/13}$ activate monomeric Rho GTPases. There are several regulating proteins that can catalyze the GDP-GTP and GTP-GDP exchange, but there are also two toxins used that can inhibit these activities. The first one

is Pertussis toxin which is a bacterial toxin that keeps the α subunit of the Gi family of G-proteins in GDP/inactive state by catalysing the ADP-ribosylation thus blocking its interaction with GPCRs. There is also the use of cholera toxin, another bacterial toxin. This toxin inhibits the GTPase activity of the α subunit of the Gs family of G-proteins keeping it in a constitutively active state by ADP ribosylating it (227,228). GPCRs are a family of intrinsic hydrophobic proteins only found in higher eurokaryotes, located both at the plasma membrane and nuclear envelope of cells (169).

The β and γ G-protein subunits, are also able to play a signalling role. For example our group has previously shown that LTD_4 stimulation of calcium intracellular release, requires the release of inositoltriphosphate from diacylglycerol. This is achieved through the action of phospholipase C –γ, which required "docking" with the β and γ subunits to become functional (229).

12. GPCR dimerization and other GPCR interacting proteins

GPCRs can signal as hetero- and/or homo-dimers or oligomers. Moreover, dimerization has been shown to be needed for proper expression, stronger ligand binding, phosphorylation and internalization.

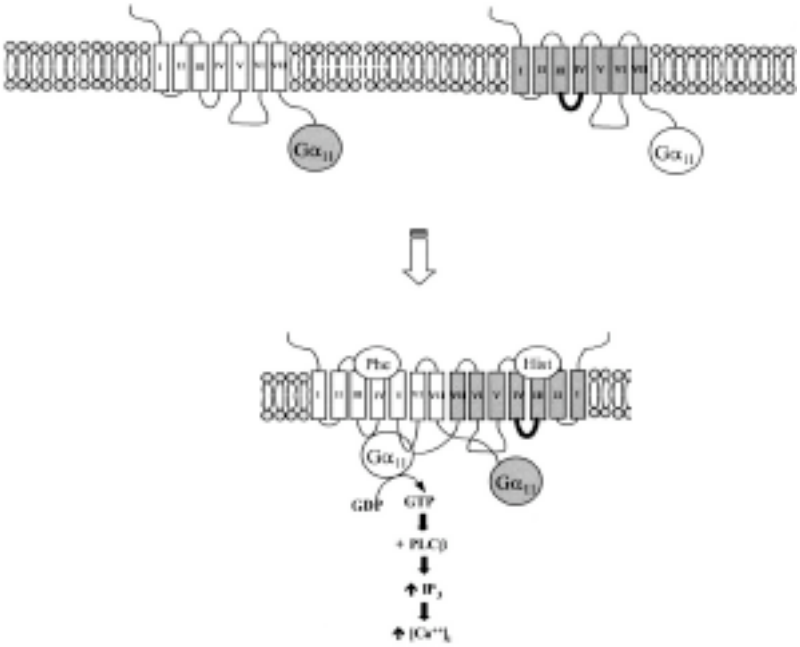

Figure9. GPCR dimerization. Modified from Carrillo, J. J. et al. J. Biol. Chem. 2003;278:42578-42587

Dimerized GPCRs have been shown to have signalling properties distinct form those of the monomeric receptors (230,231). The $GABA_B$ receptors are a part of the family C GPCRs and they brought attention to the functional relevance of receptor dimerization. It was demonstrated that when the $GABA_BR_1$ was expressed alone it did not have the ability to be efficiently trafficked to the cell surface (232). Six years after the cloning of this receptor the $GABA_BR_2$ was cloned and studies on this receptor showed that it could not bind ligands when expressed alone. However, when the two receptors were expressed together they were efficiently expressed at the plasma membrane and also able to respond to the GABA ligands (233). It has been suggested that $GABA_B$1 and 2 receptors can dimerize via the transmembrane or N-terminal regions (234). However, the $GABA_BR_1$ is found in many regions of the brain where expression of the $GABAR_2$ is not detected. (235). Surprisingly it was found that non of the mGluR (closest related family) or 30 other GPCRs could

effectively target the $GABA_B1R$ to the cell surface (236). Several other receptors have been shown to dimerize for different functions. Table 1. demonstrates various receptors, their partners and the effect of the dimerization (237).

Receptor	Heterodimer Partner	Negative Controls	Effect of Heterodimerization
$5\text{-}HT_{1B}$	$5\text{-}HT_{1D}$		n.d.
Adenosine A1	Dopamine D1	Dopamine D2	Signaling
Adenosine A1	$P2Y_1$		Pharmacology
Adenosine A1	mGluR1α	mGluR1β	Signaling
Adenosine A2A	Dopamine D2	Dopamine D1	Internalization, signaling
Adenosine A2A	mGluR5	mGluR1β	Signaling
Angiotensin 1A	Angiotensin 2		Signaling
Angiotensin 1A	β_2AR		Signaling, trafficking
Angiotensin 1A	Bradykinin B2		Internalization, pharmacology, signaling
Calcium sensing receptor	mGluR1 and mGluR5		Trafficking
CCR2	CXCR4 and CCR5		Signaling, reduction of HIV infection
CCR5	δ-, κ-, and μ-OPR		Desensitization
Cholecystokinin A	Cholecystokinin B	β_2AR	Signaling, internalization
Dopamine D1	Dopamine D2		Signaling
Dopamine D2	SSTR5		Pharmacology, signaling
Dopamine D2	Dopamine D3		Pharmacology
Endothelin A	Endothelin B		Internalization
$GABA_BR1$	$GABA_BR2$		Gain of function, pharmacology
Melatonin MT1	Melatonin MT2	β_2AR	n.d.
Muscarinic M2	Muscarinic M3		Pharmacology
Oxytocin	Vasopressin V1a and V2	$GABA_BR2$	n.d.
S1P1	S1P2 and S1P3	LPA1	n.d.
SSTR1	SSTR5	SSTR4	Internalization, pharmacology, expression
SSTR2A	SSTR3		Desensitization
SSTR2A	μ-OPR		Desensitization
Substance P (NK1)	μ-OPR		Internalization, desensitization
TRHR1	TRHR2	GnRHR	Internalization
Vasopressin V1a	Vasopressin V2		Internalization
α_{1B}AR	α_{1A}AR	β_2AR, NK1, CCR5	Internalization
α_{1B}AR	Histamine H_1		n.d.
α_{1D}AR	α_{1B}AR	α_{1A}AR	Gain of function, internalization
α_{1D}AR	β_2AR	β_1AR	Gain of function, internalization
α_{2A}AR	β_1AR		Internalization, pharmacology
α_{2A}AR	μ-OPR		Signaling
β_1AR	β_2AR		Internalization, pharmacology, signaling
β_2AR	δ-, κ-OPR		Internalization, signaling
β_2AR	β_3AR	$GABA_BR2$	Internalization, signaling
β_2AR	M71-OR		Gain of function, internalization
κ-OPR	δ-OPR	μ-OPR	Internalization, pharmacology, signaling
μ-OPR	δ-OPR		Pharmacology, signaling

n.d., not determined.

Table1. GPCR heterodimerisation. Modified from Prinster et. al. Pharmacological Reviews.

The importance of homo-dimerization has also been demonstrated as in the case of β_2ARs where interruption of the homo-dimerization decreases β_2AR induced cAMP production. (238). Targeting of GPCRs to the correct site has been shown to play an important role in homeostasis as miss localization has been demonstrated in various pathological conditions such as retinitis pigmentosa. This condition arises from intra cellular accumulation of mutant forms of the Rhodopsin receptor. Similar pathological accumulations have been demonstrated for the vasopressin and gonadotropin-releasing hormone receptors (239).

There are various proteins known to interact with GPCRs and deliver them to the cell surface, link them to their downstream effectors and ensure specificity and activation of diverse pathways. Proteins involved in regulating GPCR ER export and GPCR folding include the ER chaperons; calnexins, which help the folding of newly synthesized proteins and send improperly folded proteins to degradation. Accessory proteins cyclophilins are also involved in folding, and RAMPs are involved in ER export as well as proper folding, signalling, internalization, recycling and degradation (240). A-kinase anchoring proteins have been shown to link GPCRs to PKA or G-proteins (241,242). Some AKAPS have been shown to increase receptor phosphorylation and downstream ERK1/2 signalling whilst others have been shown to induce desensitization (242). Other proteins involved in bringing together GPCRs with their downstream effectors for rapid and efficient signalling are the Homer proteins and the InaD proteins (243). The InaD proteins contain PDZ domains, a domain known to interact with the C-termini of proteins including GPCRs (244). Scaffolding/chaperon proteins bind and recognize specific motifs on GPCRs (245). Furthermore, several motifs and domains of GPCRs have been demonstrated to be required for surface expression, nuclear localization and ER-retention (245).

13. GPCR desensitization

There are many regulatory mechanisms involved in GPCR signalling. One of which is receptor desensitization (246). This mechanism involves GPCR phosphorylation which is mediated by PKC, PKA or G-protein receptor kinases (GRKs) (247). The first two mentioned kinases directly uncouple GPCRs from G-proteins. PKC and PKA can mediate both homo and heterolouges desensitization. These two terminologies refer to whether the receptor desensitization is initiated by the ligand of the receptor or by another GPCR-ligand interaction. An example of this is the heterologous desensitization of the $CysLT_1R$ by UDP or ATP (165). This desensitization is mediated through PKC and leads to a more rapid receptor recovery than the homologous desensitization (165). In addition, PKA is capable of phosphorylating the GPCR in such a manner that it switches its binding from Gs to Gi. This has been demonstrated for the β2 adregenic receptor (β_2AR) and the prostacyclin receptor. This switch favours downstream activation of MAPKs such as ERK1/2 (248-250). GRKs only phosphorylate ligand occupied/ligand activated GPCRs. It is often associated with the classical β -arrestin dependent desensitization because GRKs are suggested to promote β -arrestin binding to the GPCR which inhibits the GPCR from further binding G-proteins (251). β-arrestins are often involved in receptor internalization (discussed below). There are four arrestins, two of which are expressed in the retina called visual arrestin and cone arrestin. The other two arrestins, β-arrestin-1/arrestin-2 and β-arrestin-2/arrestin-3 are expressed in most tissues. The importance of GRKs and β-arrestin are demonstrated in knock-out mice where various GPCR desensitization, signalling and regulation are impaired (218). Receptor desensitization can be regulated on G-protein level as well by the RGS family. These proteins accelerate the hydrolysis of GTP to GDP speeding up deactivation of the signal induced (252).

14. Internalization of GPCRs

GPCR internalization is a complex yet extensively studied mechanism involving various scaffolding and regulatory proteins. GPCRs can internalize via three known pathways; clathrin coated pits, uncoated vesicles and caveolae (253). Internalization of GPCRs is initiated by ligand binding, which leads to a conformational change initiating receptor signalling. This subsequently leads to phosphorylation of the receptor by PKA, PKC or GRKs (as discussed above). From here the GPCRs are targeted to vesicles transporting them inside the cell to translocate, recycle or be degraded. Some receptors have actually been shown to have the ability of continuing to signal or even initiate new signalling pathways from the endosomes (254). Though internalization is a series of sequentially regulated events, studies have demonstrated that various steps have the ability to determine or play a part in receptor fate. The ligand binding has the ability to determine the fate of the receptor. This has been demonstrated for example for the β -2 adregenic receptor. Under normal conditions when the receptor is activated by its ligand it predominantly undergoes recycling, however upon prolonged or repeated exposure to its ligand, the receptor is degraded (255). Different ligands have also been implicated in inducing different endocytic sorting and trafficking of the same GPCR (256).

Internalization of GPCRs and caveolin

Caveolae are 50-100nm flasked shaped membrane invaginations that are rich in cholesterol as well as the caveolin proteins (as indicated by the name) (257). There are three caveolins; caveolin1, 2 and 3. Caveolins-1 and 2 are strictly co localised and they have been implicated to require each other for proper function (258-260). It is not fully understood how receptors are targeted or internalized via caveolae or uncoated vesicles. But it is speculated that the transmembrane regions can interact with cholesterol found in caveolae or

uncoated vesicles and it has been shown that cholesterol can modulate the affinity of some GPCRs (261,262). Caveolae are localised both near and on the plasma membranes well as intracellularly. Interestingly many proteins such as the EGFR, heteromeric G-proteins, GPCRs and their interacting proteins are positioned in caveolae (263). This is thought to be a mechanism that makes signalling and trafficking of GPCRs efficient (263). However, disruption of caveolae has been shown to prevent internalization of the endothelin receptor ET_B and VIP receptors (263). Caveolin-1 in vivo and in vitro animal experiments have shown a suppressive effect of caveolin-1 in transformation and breast tumorogenesis (264,265). Contradictory to this, studies on human breast and prostate cancer show a positive correlation of caveolin-1 expression and tumorogenesis. Another study demonstrated elevated levels of caveolin-1 in adenocarcinoma of the colon whilst the adenomas and normal colonic epithelium showed little or no staining and Caveolin-2 absent (266). Conversely in another study CRC cell lines and human tumour epithelial mucosa were shown to express low or undetectable levels of caveolin-1 (267).

GPCR internalization and clathrin

Clathrin mediated endocytosis is a much more extensively studied mechanism. Clathrin coated pits are made up of clathrin heavy and light chain as well as a dozen regulatory proteins (268).

Clathrin mediated endocytosis of GPCRs usually includes the β-arrestin dependent internalization, although β-arrestin independent clathrin mediated internalization will also be addressed in this section.

When a GPCR is activated by its ligand and subsequently phosphorylated, this phosphorylation recruits β -arrestin. Phosphorylation of the GPCR has also been demonstrated to be able to determine the sorting of the receptor. This is exemplified in the case of the CXCR chemokine receptor where mutation of its phosphorylation sites inhibits it from being ubiquitinated and targeted to the lysosomes (269). Ubiquitin is known for its ability to sort

proteins to the proteosome (270), this mechanism includes GPCRs as well, but only in the biosynthetic pathway (271). In endocytic sorting, ubiquitin molecules added on to the C-terminus of the GPCRs targets them for lysosomal degradation (272) or effects the rate of internalization (273,274). The family of ESCRT proteins are highly conserved and have been demonstrated to be involved in the lysosomal sorting of GPCRs. This lysosomal sorting can be through the ubiquitin pathway but GPCRs can be sorted to lysosomes by ESCRT in the absence of ubiquitination as well. (256). This suggests that phosphorylation can be an initial step to the post translational modifications made on a GPCR upon trafficking.

Furthermore, phosphorylated GPCRs recruit β-arrestin that functions as a scaffolding protein and links the GPCR to the heavy chain of clathrin and to β2 subunit of AP-2 by directly binding to these proteins. AP-2 is a clathrin adaptor protein involved in early events of vesicle formation. AP-2 targets receptors containing tyrosine or di-leucine based motifs and binds them as well as binding clathrin coats and Eps-15 (another clathrin adaptor protein first discovered in the EGFR endocytic pathway). Inhibition of clathrin pit formation is often achieved by using dominant negative Eps-15 constructs. Eps15 has been shown to be both phosphorylated as well as ubiquitinated. The phosphorylation of Eps-15 has been connected to its role in internalization, although the role of the ubiquitination is still poorly understood (275,276). The clathrin coated pit complex recruits the large GTPase Dynamin via β -arrestin. Dynamin is involved in the pinching off the coated pit from the plasma membrane (277).

GPCR internalization and β -arrestin

β -arrestin mediated binding targets the GPCR to clathrin coated pits at the cell surface (268). Furthermore, ubiquitination of β-arrestin has been shown to promote internalization of GPCRs. This is suggested to occur through

enhancing the affinity of β -arrestin to the plasma membrane (278). Furthermore, β-arrestin also plays a role in receptor sorting. Transient binding of GPCRs to arrestin that is terminated shortly after internalization mediates a rapid recycling whilst a more prominent binding mediates a slow recycling (251,253). Once inside the cell, GPCRs can be de-phosphorylated and returned to the plasma membrane, but this requires that β-arrestin is disassociated from the GPCR. ERK 1/2 activation have been implicated in β-arrestin mediated signalling. Dominant negative mutants of arrestins have been shown to attenuate GPCR induced ERK1/2 phosphorylation (279,280). However β -arrestin has also been shown to mediate ERK1/2 signalling in parallel to effecting G-protein mediated signalling. Over-expression of arrestins attenuated G-protein mediated signalling of the angiogenesis 1 receptor (AT_1R) but increased ERK1/2 phosphorylation through the same receptor (281,282). β-arrestin has the ability of effecting the duration and magnitude of ERK1/2 signalling as well as its localization. This has been demonstrated by the fact that weak interactions between β-arrestin and GPCRs mediated ERK1/2 translocation to the nucleus, activation of transcription factors (Elk and c-Myc) and induction of proliferative/mitogenic responses. In a similar manner, stable interactions between β -arrestin and GPCRs can mediate ERK1/2 signalling with the difference that the ERK1/2 signal retained in the cytosol preventing agonist induced cell proliferation (282,283). With all this in mind some GPCR internalization has been suggested to be arrestin-independent. The LTB_4 receptor BLT_1R has been demonstrated to internalize in an arrestin independent but GRK dependent manner. In this study dominant negative constructs of GRK2 could inhibit internalization of the BLT_1R but dominant negative constructs of β –arrestins were ineffective. Furthermore, the authors demonstrated a lack of co-immunoprecipitation and co-localization of β -arrestins with the BLT_1R (284). This does not rule out the possibility that the interaction of β-arrestin and the BLT_1R might be weak and transient and therefore not detected, therefore β -arrestin double (β-arrestin-1 and-2) knock-

out mice models should be used (285,286). This has been preformed in studies with the protease activated receptor 1 where internalization is not effect and suggested to be arrestin-independent (287). Similar studies to both models mentioned above have been preformed for the $CysLT_1$ receptor, where over-expression of β -arrestin increased $CysLT_1$ internalization and dominant negative constructs of β -arrestin demonstrate a non-significant decrease of receptor internalization. However, MEF cells from β -arrestin double knockout mice demonstrated a loss of $CysLT_1$ from the surface similar to that of the wild type mice (176). We preformed β -arrestin-2 siRNA studies in intestinal epithelial and CRC cells and demonstrate an almost abolished internalization of $CysLT_1R$.

GPCR internalization and Rab proteins

The Rab GTPases are small monomeric G-proteins and constitute the largest family of monomeric GTPases with over 60 different members (288). They are involved in various cellular processes such as trafficking, endocytosis, exocytosis cell growth and differentiation (289). They are post-transitionally modified which allows them to associate with various membranes such as the Golgi-, nucleus, mitochondria-, ER-, plasma- membranes, endosomes and lysosomes (290). They act to coordinate the trafficking between these membrane bodies.

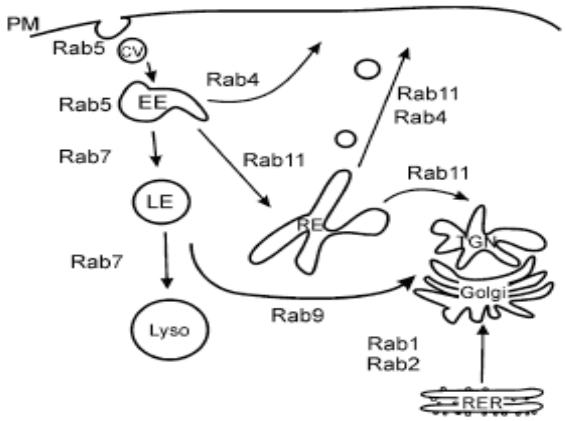

Figure11. Role of Rab GTPases in GPCR trafficking. From Seachrist et al Life sciences, 2003.

Several Rab GTPases have been shown to be involved in the internal trafficking of GPCRs. Rab 5 and Rab 21 are involved in the trafficking of clathrin coated pits and early endosomes (291) whilst Rab 7 is implicated in trafficking to late endosomes and lysosomes(246). Rab 11 and 4 have been shown to be involved in the recycling of GPCRs to the plasma membrane. Rab 4 is involved in the fast recycling whilst Rab 11 is involved in the slow recycling (292). The different Rabs are localised to specific membrane domains and translocate upon activation. Rab 5 for example is localised to the clathrin coated pits and early endosomes (289,290). Even though GPCRs may mainly localize to Rab5 in the early endosomes or clathrin coated pits, they can later be sorted to different types of endosomes controlled by different types of Rabs. This is the case for the endothelin receptors, A and B. The Endothelin A and B receptors are targeted to Rab 5 positive vesicles but Endothelin A is recycled whilst Endothelin B is degraded (293). On the other hand it has also been demonstrated that GPCRs such as the AT1AR can work as Rab protein modulators. AT1AR has been shown to stimulate Rab5 GDP/GTP exchange (290).

15. Nuclear GPCR

Over time a greater number of GPCRs have been found at the nuclear membrane and even inside the nucleus (such as the PAFR) (294). They have either been shown to be there under basal conditions such as the prostaglandin receptors (EP1-4) (295) and be further increased upon stimulation, such as the $CysLT_1R$ (169) or translocate there upon ligand dependent or independent activation (296). The GPCRs have been shown to be inserted into the nuclear membrane and exert signalling pathways or gene transcriptions that are diverse from those of the plasma membrane (297). Interestingly, no difference in the size and sequence has been detected in any of the GPCRs (297). There are several examples of GPCRs signalling at the nucleus. The first examples are GPCRs at the plasma membrane that initiate signalling pathways at the nuclear membrane. The GPCR for LPA (lisopphosphatidic acid) activates a G_i dependent pathway that results in activation of phospholipase D1 (PLD1) that in turn leads to conversion of phosphatidylcholine to DAG and phosphatidic acid (PA). The chemokine receptor CXCR4 has been shown to induce ERK1/2 nuclear transclocation and induction of transcription and proliferation in a G_i dependent manner. Both of these pathways are mediated through the plasma membrane GPCR eliciting a nuclear response from the plasma membrane (296). As discussed above β-arrestin can retain ERK1/2 in the cytoplasm and this retention can be mediated by GPCRs. The GPCR Neurokinin-1 for example has been shown to induce β-arrestin dependent retention of ERK1/2 in the cytoplasm while the β2 adrenergic receptor induces β-arrestin dependent ERK1/2 translocation (298-300). An example of different signalling pathways induced by the same receptor at the nuclear membrane compared to the plasma membrane is that of the EP3Rs. The receptors signal for cAMP or IP3 generation from the plasma membrane whereas the nuclear membrane EP3R induces calcium signals and induces gene-transcription (119,301). Moreover, stimulation of the nuclei with PAF and LPA induces a calcium dependent ERK1/2 pathway and NFκB binding to DNA. The calcium

induction induced by lipid ligands of these three nuclear localised GPCRs lead to specific gene-up regulations (119,297,301,302). PAF or LPA have been demonstrated to induce gene expression of eNOS, COX-2 and iNOS. These signalling cascades were mediated through MAPK and NFκB (297). Considering the cascade of signalling molecules that reside near or in the nuclear membrane such as; $cPLA_2$, PKC, ERK1/2, β-arrestin, 5-LO and COX-2 (which give rise to the production of lipid ligands) and calcium channels, it is not so farfetched to believe that signalling pathways can be orchestrated here. Some GPCRs contain nuclear localization signals (NLS) or even ER-retention sequences (PAFR and $CysLT_1R$) (169) yet deletion or mutation of these sequences do not change the nuclear localization of the GPCRs. In line with this there are GPCRs that do not contain any of these types of sequences, such as the LPA_1R (297). The LPA_1R has been shown in both clathrin and caveolae domains in the plasma membrane but co localizes only with caveolin in nuclear fractions. Considering the role caveolae play in bringing signalling molecules together this is rather interesting. Moreover, not all GPCRs that are found to reside at the nuclear membrane in certain tissue or cells are found to do so in other types of cell or tissue (297).

THE PRESENT INVESTIGATION

AIM

The general aim of this work was to further investigate signalling and trafficking of the cysteinyl leukotriene receptors and their role in CRC.

Specific aims of the present work

1. To explore the role of $cPLA_2$ in LTD_4 induced cell proliferation

2. To explore the regulatory mechanism of trafficking of the $CysLT_1R$ in non-transformed and CRC cells as increased expression of this receptor has been correlated with a poorer prognosis in CRC.

3. To validate the trafficking of the $CysLT_1R$ and the $CysLT_2R$ in relation to each other as increased expression of the $CysLT_2R$ has been correlated with a good prognosis and the balance and signalling of these receptors may play a role in CRC.

RESULTS AND DISCUSSION

Paper I

One of the characteristics of chronic inflammation is a continuous production of inflammatory mediators (32). LTs are inflammatory mediators derived from AA. AA is released by PLA_2s, particularly $cPLA_2$-α from the phospholipid bilayer of cellular membranes and can further be metabolized by 5-LO to produce LTs or COX-2 to produce PGs (94). Indeed previous studies from our group have demonstrated that LTD_4 is able to induce COX-2 expression as well as up-regulate LTC_4 synthase and 5-LO in intestinal epithelial cells (303). We have shown that these cells have the ability to produce CysLTs and that this production can mediate proliferation and survival in intestinal epithelial cells (148,303). Additionally, we have published data that LTD_4 can up-regulate 5-LO and LTC_4 synthase in CRC cells (303). In the first paper of this thesis LTD_4 was observed to be able to activate $cPLA_2$-α after 10 minutes of stimulation, and that this activation consists of phosphorylation of $cPLA_2$-α and its translocation from the cytosol to an intact nuclear fraction. The same study also revealed that LTD_4 in a similar fashion could induce production of $cPLA_2$-α after 90 minutes. Both these pathways are mediated through the $CysLT_1R$, a PTX sensitive G-protein, PKC, ERK1/2, p38 and require a calcium signal. The LTD_4 induced expression of $cPLA_2$-α is suggested to be mediated through NFκB as an inhibitor of this protein blocked the $cPLA_2$-α up-regulation. This is further supported by data from our group that LTD_4 can induce NFκB expression at both mRNA and protein level at 60 minutes of stimulation (unpublished data). The results from Paper I provide evidence for the theory that LTD_4 can induce its own production in intestinal epithelial and CRC cells. We also demonstrate that LTD_4 can induce cell proliferation, which has been previously shown to go through two separate pathways; one involving a PTX sensitive G-protein and one Ras dependent but PTX independent pathway. This latter pathway activated PKC-ε, Raf-1 and ERK1/2 (131). In PaperI the LTD_4 mediated proliferation reveals it to be $cPLA_2$-α

dependent. Interestingly the cPLA$_2$-α inhibitors even decreased the basal level of proliferation. Whether this cPLA$_2$-α proliferation involves a third pathway or a crosstalk with the other pathways was not clear. It is however interesting in the concept of inflammation induced cancer, that LTD$_4$ induces a rapid activation of cPLA$_2$-α and that a longer stimulation results in the production of cPLA$_2$-α and eventually proliferation of the cells. We also observed an increase of cPLA$_2$-α in CRC cells and tissue compared to non-transformed cells and tissue. This increased expression was similarly seen for COX-2 and correlates well with the theory that cPLA$_2$-α and COX-2 play a role in different malignancies including CRC, strengthening the idea that cPLA$_2$-α is the predominant source for eicosanoid production (81-83,85,86,90-92). There are however studies describing decreased cPLA$_2$-α levels in CRC. The study in this case suggests that cPLA$_2$-α is involved in apoptosis and the decreased expression of it, leads to cell survival (87,89).

Other studies including our own with colorectal patient material, contradict this data, as increased cPLA$_2$-α expression was evident. A recent study investigating a patient with cPLA$_2$-α deficiency indicated an important global role for cPLA$_2$-α in eicosanoid production and shows no malignancy in the colon (93).

PaperII

A key regulation in GPCR signalling is internalisation. Our group has previously identified two very interesting points about the CysLT$_1$R; its nuclear localisation and translocation (169) as well as its role in CRC prognosis (171). High levels of the CysLT$_1$R have been correlated with a poorer survival rate in material from CRC patients. In this context, we wanted to investigate a regulatory mechanism of the receptor in non-transformed intestinal epithelial cells compared to CRC cells. Our results showed a rapid internalisation of the receptor from the plasma membrane already at 5 minutes and recycling of the receptor back to the plasma membrane within 20 minutes after agonist removal in non-transformed cells. However, continuous

stimulation with LTD_4 up to 60 minutes increased of the expression of the receptor in a nuclear fraction in both non-transformed as well as CRC cells. We have previously published that the $CysLT_1R$ is also localised to the outer nuclear membrane (169). This internalisation and increase of the $CysLT_1R$ at the nuclear membrane is a clathrin dependent mechanism, as inhibition of clathrin blocks internalisation and $CysLT_1R$ accumulation at the nuclear membrane. Furthermore, the $CysLT_1R$ internalisation is a β-arrestin-2 dependent process as siRNA against β-arrestin-2 blocks loss of the $CysLT_1R$ from the cells surface. A previous study investigating internalisation of the $CysLT_1R$ demonstrated a PKC dependent but β-arrestin independent internalisation of the receptor (176). Another study showed that the LTD_4 induced internalisation of the $CysLT_1R$ is not PKC dependent but GRK2 dependent (165). These data suggest that the internalisation of the $CysLT_1R$ may vary in different systems. Since our study is preformed on cells endogenously expressing the receptor we believe that the internalisation route characterised in PaperII is representative for intestinal epithelial cells and CRC cells. Moreover, we present data that the internalised $CysLT_1R$ is targeted to Rab5 positive endosomes. The inhibition of clathrin led to blockade of the $CysLT_1R$ internalisation in both non-transformed as well as CRC cells. However, in the CRC cells an increase of the $CysLT_1R$ at the plasma membrane was detected. Indeed $CysLT_1R$ internalisation is delayed compared to non-transformed cells and also difficult to detect endogenously using confocal microscopy (169) and western blot analysis. Intriguingly an accumulation of the $CysLT_1R$ is detected rapidly after LTD_4 stimulation and this accumulation is clathrin sensitive. These results suggest a rapid turnover of the $CysLT_1R$ at the plasma membrane of CRC cells explaining the increase at the plasma membrane detected upon inhibition of clathrin coated pit formation and LTD_4 stimulation. FACS analysis only detects internalised $CysLT_1R$ after 20min to 1h in various CRC cells yet the accumulation of $CysLT_1R$ at the nuclear membrane is detected already 10-15 min of LTD_4

stimulation. This could be explained by a low amount of receptor being internalised from the plasma membrane at earlier time points that are difficult to detect. It does however not exclude the possibility of internal pools of the receptor translocating to both the plasma membrane as well as the nuclear membrane of CRC cells upon LTD_4 stimulation. This would also support the increased amount of $CysLT_1R$ detected at the plasma membrane fo CRC cells. As mentioned above inhibition of clathrin pit formation and stimulation with LTD_4 blocks the internalisation of $CysLT_1R$ from the plasma membrane and its up regulation at the nuclear membrane in non-transformed cells. This study also demonstrates ERK1/2 phsophorylation and cyclinD1 mRNA up regulation induced by LTD_4 in non transformed intestinal epithelial cells. Interestingly both these signalling events further increase upon inhibition of clathrin coated pit formation and LTD_4 stimulation (1h), suggesting that the signalling is mediated through the $CysLT_1R$ at the plasma membrane since this treatment renders the receptor to stay at the plasma membrane and continue signalling. In contrast to this LTD_4 induced COX-2 is inhibited by upon inhibition of clathrin coated pit formation suggesting that this signal is dependent on upon inhibition of $CysLT_1R$ internalisation. Furthermore, we speculate that the COX-2 signal is mediated through the $CysLT_1R$ at the nuclear membrane since $CysLT_1R$ seems to translocate to nuclear membrane upon LTD_4 stimulation. However, we can not exclude the possibility of $CysLT_1R$ signalling from endosomes.

PaperIII

Previous publications from our group have demonstrated different roles for LTD_4 and LTC_4. Whilst LTD_4 has been shown to induce proliferation, migration and cell survival (131-133), LTC_4 has been shown to promote cell differentiation (140). Furthermore, upregulation of the $CysLT_1R$ has been correlated with a poorer survival prognosis whilst increased $CysLT_2R$ correlates with a better prognosis (140,171). In this study we wanted to investigate the trafficking of the two cysteinyl leukotriene receptors; $CysLT_1R$

and $CysLT_2R$ upon LTD_4 or LTC_4 stimulation. We started our investigation by over-expressing the receptors alone or together in Cos-7 cells to determine the effect of each ligand on each receptor when expressed alone and when expressed together. However, when we tried to over-express the receptors alone, the localization of the receptors to the plasma membrane was disturbed. The majority of the receptors localised to a peri-nuclear region. When co-expressed, the localization of both receptors was observed correctly both at the plasma membrane as well as the nuclear membrane. These results were in direct conflict with studies preformed in Cos-7 cells over expressing $CysLT_1R$. The only difference in these studies and our study was the insertion of a signalling sequence upstream of the tagged receptor in the other studies. This sequence is inserted upstream the receptor to ensure proper expression and localization of the receptor to the plasma membrane(304). It is a cleavable sequence found naturally in certain proteins, but not GPCRs. Our results demonstrate a natural way of achieving proper localization of the $CysLT_1R$ and $CysLT_2R$. Furthermore, shRNA down regulating either receptor in non-transformed and CRC cells, rendered the majority of both receptors to be restricted to the peri-nuclear region. It is important to mention that not all receptors were miss-localised, especially in the CRC cells. The receptors detected at the plasma membrane are most likely the receptors that were already there before sh-RNA treatment. Another interesting observation was that down regulation of either receptor resulted in poor survival of the cells. This correlates well with previous data from our group demonstrating cell death in normal intestinal epithelial cells upon long-term treatment of $CysLT_1R$ inhibition. The same treatment in CRC cells resulted in decreased proliferation (148). Interestingly despite the restriction of the receptors to the peri-nuclear region of the cells, down regulation of $CysLT_1R$ did not change the expression of the $CysLT_2R$ or the other way around.

A recent study demonstrated that $CysLT_1R$ and $CysLT_2R$ can dimerize and that $CysLT_2R$ negatively regulates $CysLT_1R$ plasma membrane expression and

signalling in mast cells (183). These conflicting results may be due to tissue specificity of receptor regulation. Conflicting results by different groups have been demonstrated in the internalisation of the $CysLT_1R$. Furthermore, we hypothesize that a balance in the expression of $CysLT_1R$ and $CysLT_2R$ is most likely responsible for proper expression of the two receptors as low levels of $CysLT_2R$ has been detected in some cancer cells where the expression of the $CysLT_1R$ at the plasma membrane is not altered. Most likely a low level of $CysLT_2R$ is required for proper localization of the $CysLT_1R$ and vice versa. Furthermore, we investigated the effect of LTC_4 on both the $CysLT_1R$ and the $CysLT_2$ R. Interestingly both receptors were internalised from the plasma membrane upon LTC_4 stimulation. Moreover, a dimerization assay demonstrated that the $CysLT_1R$ and $CysLT_2R$ were dimerized both at basal levels as well as upon LTC_4 stimulation. No dynamics of either were detected at the nuclear membrane upon LTC_4 stimulation. Stimulation with LTD_4 resulted mainly in $CysLT_1R$ internalisation. Furthermore, stimulation with LTD_4 decreases the $CysLT_1R$ and $CysLT_2$ R dimerization. This correlates well with our previous results that the effect of LTD4 is mediated through the $CysLT_1R$.

SUMMARY

In summary, we have shown that:

1. LTD_4 via the $CysLT_1R$ can produce and activate cPLA2-α, which is involved in LTD_4 mediated intestinal epithelial cell proliferation.
2. $CysLT_1R$ is internalised and increased at the nuclear membrane in a clathrin, β -arrestin, Rab 5 dependent manner, and that the LTD_4 induced COX-2 requires $CysLT_1R$ internalisation.
3. $CysLT_1$ and $CysLT_2$ may need each other for proper plasma membrane localization.
4. LTC_4 internalizes both $CysLT_1$ and $CysLT_2$ receptors, whilst LTD_4 mainly internalizes the $CysLT_1R$.
5. $CysLT_1$ and $CysLT_2$ receptors can hetero-dimerize, this dimerization is decreased upon LTD_4 stimulation

POPULÄRVETENSKAPLIG SAMMANFATTNING

Inflammation är en mekanism som kroppen använder för att skydda oss mot patogener och fysiska skador i olika vävnader. Detta karaktäriseras av feber, svullnad och rodnader. Ett nätverk av specialiserade signalvägar och mediatorer initierar, reglerar och avslutar den inflammatoriska processen. Rubbning i dessa signalvägar kan leda till att inflammationsprocessen inte avslutas eller fungerar som den ska. Detta kan t.ex. hända när kroppen börjar reagera på sina egna antikroppar och detta tillstånd kallas för autoimmun sjukdom. En stor del av vårt immunförsvar sitter i mag-tarmkanalen, främst i tjocktarmen som innehåller ett stort antal bakterier. Dessa bakterier börjar leva i tarmen från det att vi föds och fortsätter föröka sig i arter allt eftersom vi utsätts för miljön och maten omkring oss. Balansen av dessa bakterier är viktig för en välfungerande tarm och ett effektivt immunsystem. Specialiserade celler i tarmen omsluter dessa bakterier och håller de skilda från immunceller och resten av kroppen. Dessa specialiserade celler består till största del av olika epitelceller som kan känna av bakterie produkter genom speciella receptorer. Dessa celler kan skilja på vilka bakterier som är egna och vilka som inte är egna. Detta medför att en låg nivå av inflammation alltid existerar i tarmen. Om epitelcellerna av olika anledningar skulle ta skada och tarmbakterierna skulle komma i kontakt med de underliggande cellerna uppstår en inflammation som karaktäriseras som akut. Men om kroppen inte kan reparera denna skada övergår den akuta inflammationen till ett tillstånd som kallas kronisk inflammation (Inflammatory bowel disease, IBD). Detta innebär att en konstant nivå av inflammation hela tiden påverkar cellerna i tarmen. Epitelcellerna kan då ta skada av det här genom muteringar i sitt DNA. Dessa muteringar leder oftast till ökad cell delning vilket i sin tur kan leda till fler muterade celler. Om tillräckligt många muteringar och muterade celler ansamlas och fortsätter delar sig kan detta leda till uppkomsten av en tumör som sedan utnyttjar de inflammatoriska cellerna för att sprida sig. Denna

fortskridning från en inflammatorisk respons till cancer är en teori som föreslogs redan 1863 av en forskare vid namn Virchow. Den är också grunden för de studier som presenteras i denna avhandling. Den modell som används är normala epitelceller och koloncancer celler och de inflammatoriska mediatorerna som undersöks är cysteinyl leukotrienerna (LTC_4, LTD_4 och LTE_4). Dessa inflammatoriska mediatorer bildas från arakidonsyra som frisätts från cellmembran främst av ett enzym kallat $cPLA_2\alpha$. Tidigare studier från vår grupp har visat att LTD4 kan inducera celldelning, cellöverlevnad samt cellmigration i normala tarmepitelceller, tre mekanismer som används av cancer celler för överlevnad. Dessa LTD_4 inducerade mekanismer har visats vara genom hög affinitets receptorn för LTD_4, nämligen $CysLT_1R$. LTC_4 har föreslagits ha en roll i celldifferentiering. Leukotrienerna har 4 olika receptorer; $CysLT_1$, $CysLT_2$, GPR17 och $CysLTE_4R$. Ett ökat uttryck av $CysLT_1R$ har påvisats i material från koloncancer patienter. Detta ökade uttryck har visats ge en dålig överlevnadsprognos medan ökat uttryck av $CysLT_2R$ ger en bättre prognos. Den första studien i denna avhandlig visar att LTD_4 via $CysLT_1R$ kan aktivera $cPLA_2$-alpha och att denna aktivering är ett av stegen i en signalväg som lever till LTD4 inducerad celldelning. Signalvägen som aktiverar $cPLA_2\alpha$ via LTD_4 har också karaktäriserats i större detalj denna studie. Vi visar involveringen av protein kinase C (PKC), MAP kinaserna; ERK1/2 och p38 samt transkriptionsfaktorn NFκB. I den andra studien har internaliseringen av $CysLT_1R$ undersökts. Internalisering av receptorer är ett nyckelsteg som definierar varaktigheten av en signalväg. Vi visar här att $CysLT_1R$ internaliseras via clathrin vesiklar, Rab5 positiva endosomer och β -arrestin-2. Utöver detta visar vi att $CysLT_1R$ ökar i kärnan och föreslår att den där kan inducera ökad COX-2 mRNA. I den tredje studien visar vi att $CysLT_1R$ och $CysLT_2R$ kan dimerisera. Vi visar även att LTC_4 kan inducera internalisering av båda receptorena, men att LTD_4 främst internaliserar $CysLT_1R$. Utöver detta visar vi att LTD_4 minskar dimeriseringen mellan $CysLT_1$ och $CysLT_2R$.

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