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PROTECTIVE ACTIONS OF LUMINALLY RESTRICTED 5-HT\textsubscript{4} RECEPTOR AGONIST IN DEXTRAN SODIUM SULFATE INDUCED COLITIS

A Thesis Presented

by

Alisha Anne Linton

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The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
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ABSTRACT

The 5-hydroxytryptamine receptor 4 (5-HT₄ receptor) is heavily expressed on colonic epithelial cells and has been targeted as a therapeutic for functional bowel symptoms and pain; however, adverse cardiac events related to 5-HT₄ agonist treatment limited their therapeutic use. Previous studies in the Mawe laboratory have demonstrated that intraluminal application of a 5-HT₄ agonist exerts protective epithelial actions in animal models of colitis, and accelerates recovery from colitis. The aim of this study was to test the effects of a luminally restricted 5-HT₄ agonist in a mouse model of experimental colitis.

The luminally restricted 5-HT₄ agonist (Takeda Pharmaceuticals; 10 mg/kg) was administered to mice during active dextran sodium sulfate (DSS) induced colitis. Colitis activity was evaluated using disease activity index, a fecal lipocalin-2 assay, and histological damage scoring. Epithelial proliferation and colonic motility were also measured as readouts of the potential protective actions and colonic function, respectively.

Oral gavage and intracolonic delivery of this luminally restricted 5-HT₄ agonist had no detectable effect on recovery from colitis or colonic motility as compared to vehicle. Additionally, in positive control experiments, we failed to see an effect of the 5-HT₄ agonist, tegaserod, on colitis severity or colonic motility in any of the measures tested.

In conclusion, it is unclear if the luminally restricted 5-HT₄ agonist has any effect on recovery from DSS colitis. Given inconsistencies with the model and lack of an effect of tegaserod, additional studies will be required, possibly involving different doses and time points, to fully assess the actions of this luminally restricted compound in colitis recovery.
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CHAPTER 1: LITERATURE REVIEW

I. Structure and Organization of the Gastrointestinal Tract

A. Organization of the Gastrointestinal Tract

The gastrointestinal (GI) tract is a long tube that begins in the mouth and ends at the anus. Each part of the GI tract is specialized to serve the overall function of the organ system, which is to breakdown ingested food into absorbable molecules, and to absorb those molecules for use as nutrients. While the GI tract has specialized parts, the basic structure of the gut wall is maintained throughout the length of the organ system. The four tissue layers of the gut are the mucosa, submucosa, muscularis externa and serosa. Additionally, the gut contains its own nervous system, the enteric nervous system, that is organized as several sets of ganglionated plexi, and that serve to coordinate the movements and functions of the gut. The myenteric (Auerbach’s) plexus is located within the muscularis externa and serves to control motor patterns, and the submucosal (Meissner’s) plexus is located within the submucosa and helps to coordinate secretion and vasodilation. The enteric nervous system is highly specialized and autonomous, receiving only moderate autonomic input from the central nervous system via the vagus nerve, sacral spinal roots S2-4, and prevertebral ganglia (celiac, superior and inferior mesenteric ganglia) within the abdominal cavity.

Starting from the mouth, food first enters the oral cavity and is mechanically broken down by mastication, and enzymatically by salivary amylase. From here, food is

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1 Information within this section is textbook material. See Silverthorn DJ, BR; Ober, WC; Garrison, CW; Silverthorn, AC (2013) Human Physiology: and Integrated Approach. Pearson.
swallowed and descends the esophagus via peristalsis, passes through the lower esophageal sphincter and enters the stomach. The stomach serves to temporarily store food, further digest food using acids, lipases and peptidases, and control the rate at which food enters the duodenum. Specialized parietal cells are responsible for maintaining the acidic environment of the stomach by secreting hydrochloric acid. The acidic environment of the stomach is important not only for helping to break down food particles, but also to kill any potential bacterial hazards. This acid, along with the other enzymes and mechanical movement, begin the process of digestion, primarily breaking down large food particles to create a soupy substance known as chyme. Chyme exits the stomach via the powerful pyloric sphincter and enters the duodenum.

The duodenum is the first part of the small intestine and secretes alkaline mucus from Brunner’s glands to neutralize the acidic pH of the semi-solid chyme exiting the stomach. Two accessory GI organs, the pancreas and the gallbladder, secrete their contents into the duodenum at the ampulla of Vater. The entrance of these substances is controlled by the small circular muscle that surrounds the ampulla, called the sphincter of Oddi. The pancreas synthesizes many digestive enzymes, and the gallbladder stores and concentrates bile which contains enzymes to help break down fats. The distal two regions of the small intestine are the jejunum and ileum, respectively. Their border is ill-defined, but differences can be noted in the thickness of the mucosa. The jejunum has a thicker, more folded mucosa, while the ileum has a thinner mucosa and the presence of Peyer’s patches, seen as mounds under the epithelium. Peyer’s patches are nodes of lymphatic tissue contained within the submucosal layer of the gut, and play an important role in
maintaining gut homeostasis. The main function of the small intestine is to further break down food particles into nutrients and then readily absorb those nutrients into the bloodstream. The mucosa of the small intestine has specialized folds to increase surface area, including mucosal folds (plica circulares in the jejunum), villi (finger-like projections of mucosa), and microvilli (on the luminal side of individual epithelial cells). These specialized folds result in a 20-30 fold increase in surface area, resulting in more efficient nutrient absorption. Additionally, peristalsis and segmentation help to mix and mechanically break down food particles. Peristalsis is a coordinated motor pattern that helps push contents forward through the gut. Segmentation occurs to help mix intestinal contents with the digestive enzymes, and to ensure that all chyme contacts the absorptive mucosa. The small intestine empties into the cecum, which is located at the base of the ascending colon. The ileocecal valve prevents retrograde movement of intestinal contents back into the small intestine.

The large intestine is the final portion of the gastrointestinal system and serves to manage waste excretion and fluid balance. The large intestine consists of the cecum, colon and rectum. In humans, the large intestine can be divided into four segments – the ascending colon, the transverse colon, the descending colon, and the sigmoid colon, which is directly followed by the rectum. In rodents, the colon has simply a distal and proximal part. The large intestine is noted for the prominent bands of longitudinal muscle running along the length of the colon called teniae coli. These bands of muscle are shorter than the length of the colon, which causes the colon to bunch. This bunching creates bulges called haustra. Additionally, the colon is histologically different than the small
intestine, containing no villi and instead having crypts of Lieberkühn, also called colonic
glands. These glands contain predominately enterocytes, but also contain more mucus
secreting goblet cells than the small intestine. Specialized Enteroendocrine cells are
generally located in the bottom third of the colonic glands. Finally, the rectum is the last
portion of the GI tract and connects to the anus. It stores intestinal contents until time for
defecation.

B. Tissues of the Gastrointestinal System

The wall of the GI tract can be divided into three layers: the mucosa, the
submucosa and the muscularis propria. Starting most centrally, the epithelium of the gut
is in contact with the contents of the lumen. Deep to the epithelium lies the lamina
propria. Deep to the lamina propria lies the muscularis mucosa and then the submucosa.
The submucosal ganglia are located within the submucosal space. Outside of the
submucosa sits the muscularis propria which contains a layer of longitudinal and a layer
of circular muscle, with the myenteric nerve plexus sitting in between.

1. Mucosa

The mucosal layer of the GI tract is comprised of three sublayers – the epithelium,
lamina propria and muscularis mucosa. The epithelial layer is a heterogeneous mix of cell
types, including enterocytes, Paneth cells, enteroendocrine cells, and goblet cells, with
the latter two only present in the stomach and intestines. These cells have specialized
functions and help to both protect the tissue, and maintain barrier function. The epithelial
layer in the oral cavity, pharynx, and esophagus is made of non-keratinized, stratified squamous epithelium, whereas the stomach and intestines contain simple columnar epithelium. Additionally, the epithelium of the stomach and intestines is organized into tubular glands, or folds. These folds help to not only increase surface area for nutrient absorption in the small intestine (plicae circulares), but also allow for expansion of the stomach to accommodate food intake (rugae), and restrict the movement of intestinal contents within the colon. The lamina propria is a layer of loose connective tissue that provides vascularization to the epithelium and houses mucosal glands and gut associated lymphoid tissues, including B and T lymphocytes and dendritic cells. Together, the epithelium and the immune cells in the lamina propria work to maintain barrier function and homeostasis within the gut. Lastly, the muscularis mucosa is a thin muscular layer beneath the lamina propria that modulates the surface area of the lumen. Contraction causes the rugae of the stomach and plicae circulares of the small intestine to decrease the available surface area, whereas relaxation of the muscularis mucosa causes those structures to expand, increasing the available surface area.

2. Submucosa

The submucosa is a rich connective tissue layer that houses the submucosal plexus of the enteric nervous system. In some areas of the gut, such as the duodenum, this layer contains glands that secrete contents into the lumen to aid in the digestive process. This layer is also rich in blood vessels and lymphatics. The submucosal plexus is responsible for coordinating secretory reflexes, as well as vasodilatory reflexes.
3. **Muscularis Externa**

The muscularis externa is comprised of two muscular layers and one ganglionated plexus. The myenteric plexus is sandwiched between a layer of circular muscle and a layer of longitudinal muscle. These two layers of muscle contract and relax in a coordinated fashion to produce motor patterns within the gut, including segmentation and peristalsis. Segmentation occurs when adjacent sections of gut contract and relax in a coordinated manner to allow for mixing of luminal contents. Peristalsis causes the forward movement of luminal contents by an upstream contraction and a downstream relaxation. These motor patterns are coordinated primarily by the myenteric plexus, with little extrinsic input from the central nervous system.

4. **Serosa**

The serosa, or adventitia layer, is a sheet like membrane covering the outside of the gut, and is made of a single layer of mesothelial cells. The parts of the GI tract that are intraperitoneal are covered with serosa, while the retroperitoneal parts, the esophagus, and the oral cavity are covered in adventitia. The serosa and the adventitia layer both serve the role of providing an external layer of tissue to these organs. The serosa is continuous with the visceral peritoneum lining the abdominal cavity. It contains blood vessels, lymphatics and nerves, and, within the intraperitoneal space, is connected to the mesentery.
II. Serotonin

A. History

The substance now known as serotonin was first isolated from rabbit gastric mucosa by the Italian pharmacologist Vittorio Erspamer in 1937 (Erspamer V, 1937). He named this bioactive amine, enteramine, as he identified it in the GI tracts of almost every vertebrate he studied. Later, a compound with vasoconstrictive properties was identified in bovine serum by researchers at the Cleveland Clinic. Maurice Rapport, Arda Green and Irvine Page called this compound serotonin due to its effect increasing vascular tone (Rapport et al., 1948). In time, these two molecules were discovered to be the same, 5-hydroxytryptamine, and the name serotonin was adopted for general use.

B. Gastrointestinal Mucosal Serotonin

Serotonin (5-hydroxytryptamine, 5-HT) is an important signaling molecule for many physiological systems, and it plays a particularly crucial role within the GI tract (Mawe and Hoffman, 2013). The mucosa of the GI tract contains the body’s largest store of 5-HT. It is synthesized from tryptophan, using the enzyme tryptophan hydroxylase-1 (TPH-1), by enterochromaffin (EC) cells within the gut epithelium. Once synthesized it is stored in intracellular granules along the basal side of EC cells until released into the lamina propria. Release can be stimulated by intraluminal changes in acidity, pressure, or increased nutrient concentration. Once within the lamina propria, 5-HT interacts with a variety of cell types, including enteric neurons, extrinsic neuron projections, epithelial
cells and immune cells. The precise action of 5-HT depends on the type of receptor that is expressed.

To terminate 5-HT signaling, molecules are removed from the extracellular space via the serotonin-selective reuptake transporter (SERT) protein. SERT is expressed on serotonergic enteric neurons and virtually all intestinal epithelial cells. Once 5-HT has been transported into cells by SERT, it is either degraded by intracellular degradative enzymes, such as monoamine oxidases, or is repackaged into vesicles. Any 5-HT not transported out of the interstitial space will enter the blood stream via the dense capillary bed in the lamina propria, and be taken up by blood platelets, which also express SERT.

Altered serotonin signaling within the GI tract is implicated in human inflammatory bowel diseases (IBD) such as Crohn’s Disease and Ulcerative Colitis. Changes in GI serotonin content, EC cell density and SERT expression have been reported in both human disease and animal models of colitis (Coates et al., 2017). It is also known that serotonin can modify GI motility and that activation of epithelial serotonin receptors has protective epithelial actions and promotes recovery from colitis (Hoffman et al., 2012, Spohn et al., 2016). It should also be noted that serotonin exerts pro-inflammatory actions in the GI tract through activation of 5-HT7 receptors on dendritic cells (Spohn and Mawe, 2017).

C. 5-HT4 Receptor

There are seven classes of 5-HT receptors (5-HT1 – 5-HT7), with 13 distinct subtypes, 7 of which are expressed in the GI tracts of humans (5-HT1A, 5-HT2A, 5-HT2B,
5-HT₃, 5-HT₄, and 5-HT₇)(Mawe and Hoffman, 2013). They have been identified on a variety of cell types within the gut, including enterocytes, goblet cells, EC cells, neurons, immune cells, smooth muscle cells and interstitial cells of Cajal. One receptor subtype, the 5-HT₄ receptor, plays an important role in gastrointestinal homeostasis and motility. The 5-HT₄ receptor is a G-protein coupled receptor, that is Gₛ coupled and activates the adenylate cyclase/cyclic adenosinemonophosphate (cAMP)/protein kinase A pathway. Thus, it plays a role in many different cellular functions including, but not limited to, prosecretory actions and facilitation of neurotransmitter release (Tonini et al., 1989, Pan and Galligan, 1994, Hoffman et al., 2012)

The 5-HT₄ receptor is expressed on enteric nerve terminals, where it helps to mediate neurotransmitter release through presynaptic facilitation (Pan and Galligan, 1994). It has also been demonstrated that 5-HT₄ receptor stimulation promotes enteric neuronal survival and neurogenesis (Liu et al., 2009). This receptor is also heavily expressed on colonic epithelial cells, where it helps to mediate 5-HT release from enterochromaffin cells, stimulates chloride secretion from enterocytes, and promotes goblet cell degranulation (Hoffman et al., 2012). Furthermore, activation of epithelial 5-HT₄ receptors has been shown to stimulate propulsive motility, decrease visceral hypersensitivity, promote epithelial proliferation and promote the integrity of the epithelial barrier (Spohn et al., 2016).
D. Mucosal 5-HT₄ Receptor Actions

There is strong evidence for mucosal 5-HT₄ receptors mediating the prokinetic, anti-nociceptive and anti-inflammatory actions within the gastrointestinal tract. The 5-HT₄ receptor is specifically expressed by a multitude of cells types in the epithelium of the GI tract, including 5-HT containing enterochromaffin (EC) cells, mucin-2 containing goblet cells and enterocytes in human and mouse tissues (Hoffman et al., 2012, Spohn et al., 2016)

1. Prokinetic Actions

5-HT₄ agonists have potent prokinetic actions that have been identified through multiple mechanisms and at multiple sites of action. Our lab previously reported that activation of EC cells with a 5-HT₄ agonist results in an increased release of 5-HT and increases in goblet cell cavitation and mucus release (Hoffman et al., 2012). It has also been shown that stimulation of the cAMP/PKA pathway in human colonic cell lines results in mucus secretion (Bradbury, 2000). This implies that mucus release could result from direct activation of mucosal 5-HT₄ receptors. Lastly, it is known that 5-HT increases chloride secretion in GI epithelium and that application of 5-HT₄ agonists to mouse colonic tissue increases the Iₛₑ current (Budhoo et al., 1996, Ning et al., 2004, Hoffman et al., 2012). Together, these three actions of 5-HT₄R activation may contribute to increasing propulsive motility of the GI tract in the following ways: (1) Increases in 5-HT release can directly activate peristaltic reflex circuitry; (2) Increases in mucus secretion may help decrease intraluminal friction, easing the passage of luminal contents; and (3)
Increases in chloride secretion result in increased water content in the lumen, softening stool and allowing for ease of passage. Furthermore, 5-HT$_4$ agonists have been shown to directly increase colonic motility in healthy and inflamed colons of guinea pig and mice by directly activating peristaltic reflex circuitry (Grider et al., 1998, Jin et al., 1999, Spohn et al., 2016). Together, these results indicate a potent prokinetic effect of 5-HT$_4$ receptor activation.

2. *Anti-nociceptive Actions*

Anti-nociceptive effects of 5-HT$_4$ agonists have been observed in rat models of hypersensitivity and in clinical trials in humans. The 5-HT$_4$ agonist tegaserod alleviates abdominal pain and discomfort in rats, as seen by a decrease in colonic hypersensitivity (Greenwood-Van Meerveld et al., 2006, Hoffman et al., 2012). Greenwood-Van Meerveld and colleagues demonstrated that rats with both acute and chronic hypersensitivity showed a decreased visceral motor response to colorectal distention after oral or intracolonic treatment with tegaserod. The response to intracolonically delivered tegaserod was blocked by pretreatment with the 5-HT$_4$ selective antagonist GR113808. Multiple clinical trials have reported a significant decrease in perceived abdominal pain, a decrease in straining and an improvement in stool consistency for IBS patients treated with tegaserod as compared to control patients (Novick et al., 2002, Chey et al., 2008). The exact mechanism by which 5-HT$_4$ activation alters visceral hypersensitivity is unknown.
3. **Protective Epithelial Actions**

Our lab has demonstrated the protective actions of mucosal 5-HT$_4$ receptors in a multitude of animal models and assays. Intracolonic tegaserod treatment decreased clinical and histological damage scores in both the 2,4,6-trinitrobenzene sulfonic acid (TNBS)(mouse and guinea pig) and dextran sodium sulfate (DSS)(mouse) models of colitis (Spohn et al., 2016). Intraperitoneal administration of a 5-HT$_4$ agonist did not provide a protective effect, and the protective and restorative effects of intracolonic treatment were blocked by antagonist treatment (Spohn et al., 2016). In addition, these effects were not present in 5-HT$_4$ deficient mice. These results suggest that activation of the 5HT$_4$ receptor is sufficient to induce a protective response in experimental colitis. Furthermore, tegaserod treatment in mice with DSS colitis improved epithelial barrier function as seen by a decrease in bacterial translocation to the spleen or liver (Spohn et al., 2016). Lastly, treatment of Caco-2 cells, a human epithelial colorectal adenocarcinoma cell line, with tegaserod resulted in increased resistance to oxidative stress, and an increased rate of cell migration following an *in vitro* scratch assay (Spohn et al., 2016). These results were blocked by antagonist treatment. Together, these actions suggest a potent protective effect of epithelial 5-HT$_4$ receptor activation *in vivo* and *in vitro*.

**E. Epithelial 5-HT$_4$ receptors as a therapeutic target**

The 5-HT$_4$ receptor has been identified as a potent therapeutic target for constipation relief in irritable bowel syndrome (IBS) and chronic constipation, as well as
pain relief in IBS; however, off-target cardiac effects have limited their use in clinical populations (Novick et al., 2002, Chey et al., 2008, Tack et al., 2012).

Agonists of the 5-HT₄R, including cisapride and tegaserod, have had remarkable clinical success for patients with constipation and constipation predominant IBD; however, their use in patient populations was suspended or restricted after reports of adverse cardiovascular events (McCallum et al., 1988, Evans et al., 2007, Tack et al., 2012).

Tegaserod was removed from the market in 2007 by recommendation from the FDA based on evidence from pooled clinical trial data suggesting a risk of ischemic cardiovascular events (Wooltorton, 2004). However, it is unknown how tegaserod led to these adverse events. Tegaserod has a low affinity for the 5-HT₁B receptor located on blood vessels, but causes vasodilation, and thus would not lead to ischemia. A large, matched-cohort study in 2010 detected no increase in ischemic cardiovascular events in tegaserod users (Loughlin et al., 2010).

Cisapride is a benzamide, with moderate affinity and poor selectivity for the 5-HT₄ receptor (Nagakura et al., 1999). It also blocks 5-HT₂, 5-HT₃, and the human ether-a-go-go-related gene (hERG)-encoded K⁺ channel (Nagakura et al., 1999, Potet et al., 2001). The hERG channel is present on cardiac smooth muscle cells, and it is thought that blockage of this channel led to a lengthening of the QT interval, causing the adverse cardiac events, particularly in individuals with long QT syndrome (Drolet et al., 1998). While 5-HT₄ agonists other than cisapride have shown to have low to no-binding capacity for the hERG-K⁺ channel, or other K⁺ or Na⁺ channels, there is still a stigma
and fear associated with serotonin receptor agonists as a therapeutic target (Tack et al., 2012). Since these side effects were a result of systemic availability, a therapeutic in which the active compound is not absorbed systemically could yield the same efficacy without the potential for dangerous off-target effects.

II. Inflammatory Bowel Disease

Inflammatory Bowel Disease (IBD) is a condition of chronic or relapsing/remitting inflammation of the gastrointestinal tract. IBD is an umbrella term that includes Crohn’s disease (CD) and Ulcerative Colitis (UC). This disease typically manifests between the second and third decade of life, and predominately affects women over men. According to the CDC, in 2015 the prevalence of IBD diagnosis was 1.3% (3.1 million) of U.S. adults, which increased from 0.9% (1.8 million) in 1999. This study showed a higher prevalence in adults over the age of 45, Hispanics, non-Hispanic whites, and adults with a less than high school education (Dahlhamer, 2016). However, other studies have shown increased prevalence at higher socioeconomic levels (Krishnan and Korzenik, 2002).

There is extensive physical and financial burden on those suffering from IBD. According to a 2008 study, the average annual cost for those suffering from IBD is between $5000 and $10,000 (Kappelman et al., 2008). Additionally, there is a higher hospitalization rate for individuals with IBD, and most patients will require surgery at least once in their lifetime (Bewtra et al., 2007). There is no current cure of IBD, only life-long palliative treatments.
The etiology of IBD is unknown. It is thought that a combination of altered gut microbiota and aberrant mucosal immune responses due to diet and environmental factors in genetically susceptible individuals leads to development of IBD (Matsuoka et al., 2018). There have been 163 susceptibility loci identified for IBD, including approximately 300 potential genes (Loddo and Romano, 2015). The first IBD associated gene discovered was for nucleotide-binding oligomerization domain containing 2 (NOD2), which codes for an intracellular pattern recognition receptor. Bacterial binding to this protein induces autophagy in dendritic cells, and mutations in this protein are associated with CD (Cooney et al., 2010). There is a prominent familial component to IBD, with relatives of CD or UC having an 8- to 10-fold greater risk for developing IBD, and there is concordance between twins (Cho and Brant, 2011). The immunopathogenesis of IBD is still being elucidated, and is vastly complex. Simply, it appears that CD is primarily T_{H}1 mediated and UC is primarily T_{H}2 mediated; however, there is significant overlap in their immunologic profiles (Wallace et al., 2014). CD and UC share overlapping etiologies, but they differ anatomically and histologically, as described below.

A. Crohn’s Disease

Crohn’s disease (CD) can affect any part of the gastrointestinal tract, but commonly affects the distal small intestine, and the proximal colon. It is characterized by discontinuously affected areas of inflammation, transmural immune cell infiltration and fistulas. The major symptoms of Crohn’s include diarrhea, abdominal
pain, weight loss, fever, and less frequently bloody or mucus covered stool. Genetically, CD is primarily associated with genes for lymphocyte chemotaxis and trafficking genes (Franke et al., 2010).

B. Ulcerative Colitis

Ulcerative colitis (UC) most prominently affects the colon, primarily the distal side, and has a continuous area of inflammation. Histologically, the inflammation only affects the mucosal layer, leaving the deeper layers of the gut unaffected, and often forms erosions. The major symptoms of UC include recurrent bloody diarrhea, abdominal pain and frequent bowel movements. Genetically, UC is associated with genes that regulate barrier function, including proteins involved in epithelial tight junction integrity (Anderson et al., 2011). UC is also associated with an increased risk in colon cancer.

C. Current Therapies

The predominant current therapies for IBD include anti-inflammatory, immunosuppressive, and biologic therapies (Neurath, 2017). Anti-inflammatory drugs include 5-aminosalicylates (5-ASAs) and corticosteroids. While both are effective at inducing remission, only 5-ASAs help to maintain remission. Immunosuppressive therapies, including azathioprine, methotrexate and cyclosporin-A, have efficacy inducing and maintaining remission of both CD and UC. Lastly, biologic therapies, including monoclonal antibodies that target tumor necrosis factor (TNF)-alpha
(infliximab, adalimumab, golimumab and certolizumab pegol), have been used to induce and maintain remission in UC and CD. Studies have shown that combined immunosuppressive and biologic therapies are more effective at inducing and maintaining remission than either therapy alone for both UC and CD (Colombel et al., 2010, Panaccione et al., 2014).

Given the complex etiology and the varied cytokine profiles of IBD patients, it is challenging to find the appropriate therapeutic for a given individual. Approximately 30-50% of patients do not respond to anti-TNF agents, and there is a significant risk of relapse after discontinuation of anti-TNF therapy (40% in CD and 28% in UC) (Olesen et al., 2016, Neurath, 2017). To fill this void, many new therapeutic targets are currently being studied, including integrin blockers and modulators of T-cell trafficking (alpha-4beta-7, beta-7, MAdCAM1, and S1P receptor agonists), matrix metalloprotease inhibitors to mediate fibrosis and tissue remodeling (MMP 9 inhibitors CHST15 siRNAs), blockers of transcription factors and modulators of barrier function and anti-inflammatory pathways (Neurath, 2017).

The therapies described above are useful, but up to 40% of patients still experience other functional bowel symptoms, even when the disease is in remission (Coates et al., 2013, Vivinus-Nebot et al., 2014). These functional bowel symptoms include abdominal pain and changes in bowel habits that, while not inherently dangerous, severely affect the patient’s quality of life. Traditional therapies are targeted at dampening the immunological component of IBD; however, there is a
clear need for novel therapies targeting these functional bowel symptoms experienced by most patients.

III. Animal Models of Colitis

There is no perfect animal model that recapitulates all features of human inflammatory bowel disease; however, there are a few different models that have key features of IBD. These models include the chemically induced models: dextran sodium sulfate, TNBS, and oxazolone; and spontaneous colitis in interleukin(IL)-10 deficient mice (Kiesler et al., 2015, Wirtz et al., 2017). These methods all reproduce histological, pathological and immunologic hallmarks of inflammatory bowel diseases, the details of which are described below:

A. Dextran Sodium Sulfate

DSS colitis is induced by oral administration of the sulfated polysaccharide dextran sodium sulfate. This experimental colitis recapitulates the clinical and inflammatory features of ulcerative colitis (Okayasu et al., 1990). The exact mechanism is not entirely understood, but it is thought that the molecule is taken up into epithelial cells, altering tight junction proteins, and leading to compromised barrier function. The increased epithelial permeability allows luminal bacteria and their by-products to interact with mucosal and submucosal immune cells, resulting in rapid and intense inflammation. It has been hypothesized that DSS creates nano-lipocomplexes with fatty acids that fuse to the membranes of epithelial cells, and
penetrate the cell membrane, depositing DSS molecules intracellularly, thus affecting barrier permeability (Laroui et al., 2012). These changes in barrier function are likely due to alteration in tight junction protein expression. It has been shown that DSS can alter ribosome interactions (Miyazawa et al., 1967). Furthermore, it is known that the cytokines IL-1β and IL-18 play crucial roles in the development of DSS colitis, and that the NLRP3 inflammasome is necessary for DSS colitis to develop, indicating a role for the innate immune system (Bauer, 2010). Additionally, immune deficient mice are susceptible to DSS, showing that the adaptive immune system is not required for this immune response (Dieleman et al., 1994); however, T_{H1} and T_{H2} cytokines are present in experimental models of chronic colitis (Dieleman et al., 1998). DSS induced colitis is an acceptable model to study the features of ulcerative colitis, particularly impaired barrier function.

B. Trinitrobenzine Sulfonic Acid

TNBS is a haptenizing agent that is administered intracolonically with ethanol. The ethanol allows the TNBS to access the epithelial cells and penetrate the gut wall. TNBS colitis predominately recapitulates the features of CD, including infiltration of CD4^{+} T-cells and neutrophils, transmural inflammation, spontaneous resolution of inflammation, fibrosis of the mucosal tissue, severe diarrhea, weight loss and rectal prolapse (Neurath et al., 1995, Kiesler et al., 2015). Additionally, TNBS colitis and CD are both characterized by a T_{H1} and T_{H17} CD4^{+} T-cell dominant response, involving cytokines IFN-γ and IL-17 (Strober and Fuss, 2011).
This experimental colitis model has been particularly useful in studying the role of the adaptive immune system and T cell responses in inflammatory bowel disease. However, the role of the innate immune system should not be understated, as immune deficient mice are still susceptible to TNBS administration (Fiorucci et al., 2002). This is because IL-12 production by innate cells is necessary to drive the T-cell response.

C. Other Models of IBD: IL-10 knockout and Oxazolone colitis

Interleukin-10 knockout mice spontaneously develop colitis between 4 and 8 weeks of age, with inflammation featuring infiltration of lymphocytes, macrophages and neutrophils into the intestinal mucosa (Kuhn et al., 1993). This model has been useful for assessing immunoregulation and macrophage involvement in gut homeostasis. The inflammatory response in IL-10−/− mice is initially driven by T\textsubscript{H}1 cells and related cytokines; however, this response slowly subsides and a T\textsubscript{H}2, IL-4 and IL-13 driven response becomes the dominant profile (Spencer et al., 2002). This phenomenon gives insight into the dynamic changes in immunoregulation occurring in gut inflammation that may parallel human IBD.

Oxazolone is another haptenizing agent that, when applied intracolonicly induces colonic inflammation. The features of oxazolone colitis align with features of UC both morphologically and immunopathologically. It causes superficial inflammation of the mucosa within the distal colon, including infiltration of lymphocytes and neutrophils, and erosions (Boirivant et al., 1998). It is characterized
by a Th2 cytokine profile, including IL-13 secretion from CD4+ natural killer T cells in the lamina propria (Heller et al., 2002). IL-13 is known to cause and increase epithelial cell apoptosis, an increase in the pore-forming tight junction protein claudin-2, a decrease in the tight junction protein tricellulin and ultimately decreased barrier function (Heller et al., 2005, Krug et al., 2017). This model is useful for studying the immunopathogenesis of UC.

IV. Specific Aims

Serotonin is a very important signaling molecule within the gastrointestinal (GI) tract. One receptor subtype, the 5-HT4 receptor, has been identified as a potent therapeutic target for functional bowel disease and pain. Agonists of the 5-HT4 receptor, including cisapride and tegaserod, have had remarkable clinical success as prokinetic agents; however, adverse side effects due to systemic availability led to their removal from the market. Our lab has recently discovered that 5-HT4 receptors are highly expressed in the colonic epithelium, and that activation of these receptors promotes motility and induces protective epithelial actions (Hoffman et al., 2012, Spohn et al., 2016). We hypothesize that the administration of luminally restricted 5-HT4 agonists will accelerate recovery from established colitis by inducing protective epithelial actions and restoring normal motility patterns.

Aim 1: Evaluate the effect of luminally restricted 5-HT4 agonists on disease severity in DSS colitis. Hypothesis: Administration of luminally restricted 5HT4 agonists by enema will exert protective epithelial actions in the murine model of DSS induced colitis.
A recovery paradigm will be used to test this hypothesis. The recovery paradigm will test whether 5-HT₄ agonist treatment, initiated after DSS colitis is established, accelerates recovery from colitis. Outcome measures will include daily recordings of disease activity index, fecal lipocalin-2 levels, analysis of epithelial proliferation, and histological damage scores.

**Aim 2: Evaluate the effect of luminally restricted 5-HT₄ agonists on colonic motility in DSS colitis.** *Hypothesis: Application of a luminally restricted 5-HT₄ agonist will increase colonic motility in vivo.* This hypothesis will be tested using in vivo techniques to elucidate functional outcomes of the luminally restricted agonist. Two assays will be used to assess gastrointestinal function in DSS mice treated with the non-absorbable 5-HT₄ agonist: colonic motility and fecal output and consistency. These assays will be performed throughout the DSS recovery paradigm.

The proposed studies are designed to elucidate the effects of luminally restricted 5-HT₄ agonists on development of and recovery from colitis. We will use well validated in vivo assays to determine the protective epithelial actions of this compound on the gastrointestinal tract. These studies will examine the therapeutic potential of luminally restricted 5-HT₄ agonists for the treatment of IBD.
Works Cited


CHAPTER II: PROTECTIVE ACTIONS OF LUMINALLY RESTRICTED 5-HT4 RECEPTOR AGONISTS IN DEXTRAN SODIUM SULFATE INDUCED COLITIS

I. Abstract

Background: The 5-hydroxytryptamine receptor 4 (5-HT4 receptor) is heavily expressed on colonic epithelial cells and has been targeted as a therapeutic for functional bowel symptoms and pain; however, adverse cardiac events related to 5-HT4 agonist treatment limited their therapeutic use. Previous studies in the Mawe laboratory have demonstrated that intraluminal application of a 5-HT4 agonist exerts protective epithelial actions in animal models of colitis, and accelerates recovery from colitis. The aim of this study was to test the effects of a luminally restricted 5-HT4 agonist in a mouse model of experimental colitis.

Methods: The luminally restricted 5-HT4 agonist SYR313832Z (Takeda Pharmaceuticals; 10 mg/kg) was administered to mice during active DSS colitis. Colitis activity was evaluated using disease activity index, a fecal lipocalin-2 assay, and histological damage scoring. Epithelial proliferation and colonic motility were also measured as readouts of the potential protective actions and colonic function, respectively.

Results: Oral gavage and intracolonic delivery of SYR313832Z had no detectable effect on recovery from colitis or colonic motility as compared to vehicle. Additionally, in positive control experiments, we failed to see an effect of the 5-HT4R agonist, tegaserod, on colitis severity or colonic motility in any of the measures tested.
Conclusions: In conclusion, it is unclear if the luminal restricted 5-HT₄ agonist SYR313832Z has any effect on recovery from DSS colitis. Given inconsistencies with the model and lack of an effect of tegaserod, additional studies will be required, possibly involving different doses and time points, to fully assess the actions of SYR313832Z in colitis recovery.

II. Introduction

Serotonin (5-hydroxytryptamine, 5-HT) is an important signaling molecule for many physiological systems, and it plays a particularly crucial role within the gastrointestinal (GI) tract. Within the GI tract, 5-HT acts as a neurotransmitter and paracrine signaling molecule to stimulate motility, secretion, vasodilation and sensation (Mawe and Hoffman, 2013). Altered serotonin signaling within the GI tract is implicated in human inflammatory bowel diseases (IBD), such as Crohn’s Disease and Ulcerative Colitis (Coates et al., 2017). Serotonin receptors have been the target of therapies for functional gastrointestinal disorders and pain (Mawe and Hoffman, 2013). Unfortunately, use of many of these therapies was suspended or restricted due to reports of adverse cardiovascular events (De Maeyer et al., 2008).

Serotonin exerts its effects through activation of a family of G-protein coupled receptors. One receptor, the 5-HT₄ receptor, is a G-protein coupled receptor, that is Gₛ coupled and activates the adenylate cyclase/cyclic adenosine monophosphate (cAMP)/protein kinase A pathway. The 5-HT₄ receptor, is expressed on enteric nerve terminals, where it helps to mediate neurotransmitter release through presynaptic
facilitation, and is amply expressed on colonic epithelial cells, where it mediates 5-HT release from enterochromaffin cells, stimulates chloride secretion and goblet cell degranulation (Pan and Galligan, 1994, Hoffman et al., 2012). Furthermore, activation of mucosal 5-HT₄ receptors has been shown to stimulate propulsive motility, decrease visceral hypersensitivity, promote epithelial proliferation and promote the integrity of the epithelial barrier (Spohn et al., 2016). In the outer layers of the intestines, 5-HT₄ agonist stimulation has been shown to promote neuronal proliferation and survival, and to enhance growth of nerve fibers (Liu et al., 2009, Matsuyoshi et al., 2010, Belkind-Gerson et al., 2015).

The 5-HT₄ receptor, has been identified as a potent therapeutic target for constipation relief in irritable bowel syndrome (IBS) and chronic constipation, as well as pain relief in IBS (Novick et al., 2002, Chey et al., 2008, Tack et al., 2012). Studies from our lab have shown that intracolonic administration of the 5-HT₄ agonist, tegaserod, improves colitis recovery over intraperitoneal administration in experimental models of colitis (Spohn et al., 2016).

This study examined the hypothesis that a luminally restricted 5-HT₄ agonist, SYR313832Z, would exert protective epithelial actions and restore normal motility patterns in murine dextran sodium sulfate induced colitis. We used a recovery paradigm to investigate whether treatment of animals with active colitis would accelerate recuperation. Outcome measures included recording disease activity index, examining levels of fecal lipocalin-2, histological damage scoring, assessing epithelial proliferation,
and measuring colonic motility. The measures tested in this study reveal no effect of the luminally restricted agonist on colitis.

III. Methods

Animal Care and Use

All experimental protocols were approved by the Institutional Animal Care and Use Committee of the University of Vermont. The animals used in this study were 8-10 week-old male CD-1 IGS mice (Charles River Laboratories, Saint-Constant, QC, Canada). Animals were euthanized using isoflurane overdose followed by exsanguination.

Experimental Paradigms

For these studies, the protective epithelial actions of the proprietary, luminally restricted 5-HT₄ agonist, SRY313832Z (832Z), were assessed in a paradigm modeling recovery from induced colitis. 832Z was given to us by Takeda Pharmaceuticals for the purposes of this study. Pharmacokinetics analyses by Takeda indicate that 832Z is not detectable in the blood serum and it is heavily detected in colonic tissue up to 8 hours after gavage administration.

Colitis was induced by addition of 3% or 4% DSS to the drinking water on days 0 through 5. On day 5, DSS water was replaced with tap water. Starting on day 5, mice received daily administration (gavage or enema) of 832Z, tegaserod (positive control) or vehicle for 10 consecutive days (see Table 1 for formulations). Mice were euthanized on
day 15, and colon sections taken for histology and immunohistochemistry. To assess levels of inflammation and colitis severity the following assays were used: disease activity index score, histological damage score, and fecal lipocalin-2 levels. The measures of colonic motility included fecal water content, fecal output and bead expulsion. Any differences in the paradigm or drug administration protocol are noted in the figure legends.

<table>
<thead>
<tr>
<th></th>
<th><strong>Gavage</strong></th>
<th><strong>Enema</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle</strong></td>
<td>1% Tween80, 0.5% Methyl Cellulose in tap water</td>
<td>1% DMSO in 0.9% saline</td>
</tr>
<tr>
<td><strong>832Z</strong></td>
<td>10 mg/kg 832Z, 1% Tween80, 0.5% Methyl Cellulose in tap water</td>
<td>1 or 10 mg/kg 832Z, 1% DMSO in 0.9% saline</td>
</tr>
<tr>
<td><strong>Tegaserod</strong></td>
<td>N/A</td>
<td>1 mg/kg tegaserod, 1% DMSO in 0.9% saline</td>
</tr>
</tbody>
</table>

Table 1. Drug and vehicle formulations for 15 day recovery paradigm.

**Disease Activity Index**

Disease severity was assessed using a rubric score throughout the course of the disease paradigm. This rubric includes the major pathological landmarks of colitis: weight loss, stool consistency, and fecal blood. Each symptom is rated on a scale from 0 to 4; with a score of 4 being the most severe. The exact scoring criteria were adapted from Cooper et. al. and is described in Table 2 (Cooper et al., 1993). This score was taken every other day throughout the experimental paradigm to track the progression of the colitis. For the sake of this study, a score of 4-8 is considered moderate colitis, whereas a score greater than 8 is considered severe colitis.
<table>
<thead>
<tr>
<th>Score</th>
<th>Weight Loss</th>
<th>Stool Consistency</th>
<th>Occult/gross bleeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>1</td>
<td>1-5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5-10%</td>
<td>Loose stool</td>
<td>Hemoccult +</td>
</tr>
<tr>
<td>3</td>
<td>10-20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>&gt;20%</td>
<td>Diarrhea</td>
<td>Gross bleeding</td>
</tr>
</tbody>
</table>

Table 2. Details of disease activity index rubric.

**Fecal Lipocalin-2 ELISA**

Fecal pellets were collected over the course of the experiment and stored at -20 degrees Celsius. To prepare samples for the assay, fecal pellets were homogenized in 0.1% Tween20/PBS at 50 mg/mL, and then centrifuged for 5 minutes at 20,000 x g. Supernatant was collected and diluted from 1:5 to 1:6000 depending on the time point of the sample. Two dilutions were performed for each sample using the kit-recommended diluent (1% BSA in PBS). Lipocalin-2 levels were determined using a solid phase sandwich ELISA (Mouse Lipocalin-2/NGAL DuoSet ELISA kit, R&D Systems, Minneapolis, MN), and levels compared between the treatment and control groups at all time points. Dilutions that presented the most accurate duplicates and that fell within the standard curve of the ELISA were used for analysis.

**Histological Damage Score**

Histological assessment of tissue damage is a classic method to determine the extent of colitis. For this measure, small pieces of distal colon were fixed in 4% PFA and 0.1M sodium phosphate, paraffin embedded, sectioned, and stained using a hematoxylin and eosin (H&E) stain. Sections were blindly scored according to a scoring rubric that is
based on the classic histological features of human inflammatory bowel disease (Villanacci et al., 2013, Spohn et al., 2016). Briefly, the rubric considers infiltration of immune cells, cytoarchitecture, crypt architecture, epithelial integrity and ulcerations. Scores were compared between treatment and control groups by an unpaired students t-test or one-way ANOVA, as appropriate.

**Proliferation Assay**

Epithelial cell proliferation was assessed using immunohistological staining for the post-mitotic marker Ki-67, a technique that has been used previously to assess epithelial proliferation in human and animal models of colitis (Joly et al., 2009, Hoffman et al., 2012, Spohn et al., 2016). Paraffin-embedded sections of distal colon (same as used for H&E staining), were co-stained for Ki-67 and the nuclear marker DAPI. Within each crypt, the ratio of Ki-67+ cells:DAPI+ nuclei was counted. Three crypts were analyzed per tissue section, and then averaged to give a percent of Ki-67+ cells per crypt. These numbers were compared between groups using an unpaired students t-test.

**Colonic Motility**

The bead expulsion assay is an *in vivo* assay to assess colonic motility. This assay has been used previously to assess *in vivo* colonic motility in DSS colitis (McClain et al., 2014, Spohn et al., 2016). Briefly, the assay was performed by inserting a glass bead 2 cm into the rectum of a lightly anesthetized mouse and recording the latency from waking of the animal to expulsion of the bead. Bead expulsion data were collected from each
mouse before, during and after inflammation (approximately days 0, 5, and 15). This technique allowed for an in vivo measurement of colonic motility at multiple time points. Expulsion times shorter than 30 seconds and longer than 40 minutes were excluded. Expulsion times were either averaged and compared between groups using an unpaired students t-test, or normalized to the day 0 expulsion time, averaged and compared between groups over time using a two-way ANOVA.

**Fecal Output and Water Content**

Fecal output is the measurement of number of fecal pellets produced during one hour. To measure fecal water content, all pellets were collected during the fecal output assay and immediately placed into closed Eppendorf tubes. At the end of one hour, the total wet weight of all pellets was recorded. Pellets were then dried overnight at 50 degrees Celsius, and the dry weight was obtained the following day. The longer it takes a pellet to pass through the colon, the dryer the pellet will be (i.e. more time for water absorption leads to lower water content in the feces). Additionally, inflammation of the colon affects the absorption and secretion action of the epithelium, and thus inflammation of the colon also leads to increased water content. Fecal output and fecal water content were assessed over the course of the experimental paradigm, and results were compared between vehicle and treatment groups.
**Data Analysis**

Data are shown as mean +/- SEM for n number of animals. All data analysis was completed using GraphPad Prism software (version 7.0; GraphPad Software, La Jolla, CA). Data sets were examined before analysis to ensure that test assumptions were met (variability and n values per group). Significance was determined using unpaired students t-test, one-way ANOVA, or two-way ANOVA, with corrections for multiple comparison, where appropriate. Statistical significance was defined as P values of less than 0.05.

**IV. Results**

**Effect of Treatment on Disease Activity**

Disease activity index (DAI) is an in vivo assay of disease severity that can be taken at multiple time points throughout the course of colitis development and recovery. It is common practice in the field to utilize such a rubric to understand disease progression and recovery (Spohn et al., 2016, Wirtz et al., 2017). We tested whether intracolonic treatment of 832Z (10 mg/kg) would improve recovery from colitis, decreasing the DAI relative to the DAI of vehicle treated animals. This effect has previously been seen with intracolonic administration of tegaserod, was blocked by antagonist pre-treatment, and was not seen in 5-HT4 knockout mice (Spohn et al., 2016).

In the current study, DAI was assessed approximately every other day over the 15-day paradigm (3% DSS for 5 days, 10 days treatment). There was no significant effect of either treatment (Figure 1A and 1B). Many other iterations of this paradigm were performed with different drug delivery methods, different concentrations of drug, and
different concentrations of DSS, and similar results were obtained (Supplemental Figures 1-4).

**Effect of treatment on Histological Damage**

Clinically diagnosis of colitis typically involves histological evaluation of patient biopsies to determine the extent of inflammation. In experimental colitis, histological evaluation of mucosal architecture and neutrophil infiltration is a common method used to determine the extent of disease (Wirtz et al., 2017). Other methods, such as endoscopy, allow for longitudinal evaluation of mucosal health; however, evaluation of histological damage is the most robust readout. Given previous reports from our lab of improved histological damage with the 5-HT$_4$ receptor agonist tegaserod, we tested whether histological damage would be alleviated by the 5-HT$_4$ agonist 832Z.

We found no significant difference in histological damage scores between groups (Figure 1C). Many other iterations of this paradigm were performed with different drug delivery methods, different concentrations of drug, and different concentrations of DSS, and comparable results were obtained (Supplemental Figures 1-4).

**Effect of treatment on Epithelial Proliferation**

Human and experimental colitis is associated with degradation of the epithelial barrier. It has previously been shown that treatment with a 5-HT$_4$ agonist promotes epithelial proliferation in vitro and in vivo, resulting in improved barrier function and improved histological appearance (Spohn et al., 2016). Thus, we expected that
intracolonic treatment with the luminally restricted 5-HT₄ agonist would result in an increase of recently divided epithelial cells.

Our results indicate that there is no effect of treatment with 832Z on epithelial proliferation (Figure 1D). Many other iterations of this paradigm were performed with different drug delivery methods, different concentrations of drug, and different concentrations of DSS, and similar results were obtained (Supplemental Figures 1-4).

**Effect of treatment on fecal lipocalin-2 levels**

Recently, lipocalin-2 (Lcn-2), also known as neutrophil gelatinase-associated lipocalin in humans, has been identified as a non-invasive and sensitive biomarker of intestinal inflammation in TNBS, DSS, and IL-10 knockout experimental colitis (Chassaing et al., 2012, Hsieh et al., 2016). Fecal lipocalin levels are correlated with disease severity and pro-inflammatory cytokine levels in DSS-induced colitis and spontaneous colitis in IL-10 deficient mice (Chassaing et al., 2012). We tested whether Lcn-2 levels increased with induction of colitis, and then decreased as mice recovered from colitis. Additionally, we tested whether Lcn-2 levels for animals treated with 832Z and tegaserod returned to baseline faster than vehicle treated animals. To our knowledge, this is the first time lipocalin levels have been tested in CD-1 mice in response to induction of DSS colitis, and more importantly, used to assess the efficacy of therapeutic administration.

We found there was an increase of Lcn-2 levels in response to 3% DSS administration, but no return to baseline during the recovery phase of the paradigm.
(Figure 1E; significant effect of day, p=0.038 by two-way ANOVA). With induction at 3% DSS, Lcn-2 levels increased to ~10,000 ng/g feces by day 10 post-induction, and remained high through day 15. There were no significant differences between vehicle and agonist treated groups (Figure 1E). A preliminary study was conducted using 2.5% and 3% DSS, and assessing Lcn-2 levels in untreated mice out to day 25. By day 10, levels rose to ~ 7000 ng/g, and only dropped to ~1000 ng/g by day 25 (Supplemental Figure 5; not significant). Many other iterations of this paradigm were performed with different drug delivery methods, different concentrations of drug, and different concentrations of DSS, and similar results were obtained (Supplemental Figures 1-4).

Effect of treatment on colonic motility

It has been established that clinical IBD and experimental colitis models are associated with abdominal pain and changes in colonic motility and stool frequency (Linden et al., 2004, Hoffman et al., 2011, Vivinus-Nebot et al., 2014, Spohn et al., 2016). In animal models, it has been shown that colonic motility is decreased in colitis and is associated with inflammation induced neuroplasticity (Hoffman et al., 2011, Roberts et al., 2013). Additionally, it has been shown that treatment with a 5-HT4 agonist rescues this slowing of colonic motility in mice and guinea pigs (Spohn et al., 2016). Thus, we tested whether treatment with 832Z affected colitis induced dysmotility.

We found no changes in latency of bead expulsion between vehicle and treatment groups when colitis was induced with 3% DSS (Figure 1F). Interestingly, we also did not see the expected slowing of motility from days zero to five in response to colitis
induction. This slowing of motility was noted in one experiment in response to 4% DSS, with a significant effect of treatment (Supplemental Figure 1E; significant effect of treatment, p=0.0098, by two-way ANOVA). Many other iterations of this paradigm were performed with different drug delivery methods, different concentrations of drug, and different concentrations of DSS, and similar results to that of 3% colitis induction were obtained (Supplemental Figures 1-4).

Fecal output and fecal water content were only assessed in the first iteration of this study (Supplemental Figures 1F and 1G). This experiment, along with others in our lab, revealed that CD-1 mice have relatively high fecal water content at baseline (~60%) as compared to C57BL6/J (data not shown). Given this finding, in addition to the fact that diarrhea is a primary read out of colitis, we decided to discontinue this assay in the colitis models. Additionally, bead expulsion appeared to be a more robust measure of colonic motility than fecal output. Therefore, this assay was discontinued as well.

V. Discussion

This study tested the hypothesis that luminally restricted 5-HT₄ agonists would induce protective epithelial actions in DSS-induced experimental colitis. The results of this study failed to support the hypothesis. With the conditions that were tested, the luminally restricted 5-HT₄ agonist did not exert protective effects detectable by our outcome measures. Given previous research, these results are surprising and lead us to believe that this study may not have involved conditions optimal for activity of the luminally restricted agonist 832Z.
Based on the results reported here, it appears that 832Z does not exert the same protective actions that have previously been published for the 5-HT₄ agonist tegaserod (Spohn et al., 2016) Theoretically, this compound should stimulate the 5-HT₄ receptor and initiate the same protective actions – including stimulating epithelial proliferation, mucus secretion and propulsive motility. Additionally, pharmacokinetic analysis of 832Z performed by Takeda, indicate that this compound is present in colon tissue and the colonic lumen up to 8 hours after gavage administration. While this does not indicate that the drug is active once it reaches the colon, it does imply that there is compound binding to receptors in the wall of the lumen. In our studies, delivery of the compound via enema ensured that the compound was reaching mucosal receptors without being altered by transit through the stomach and the small intestine. However, even with enema administration, no effects of receptor stimulation were seen. This lack of an effect could be explained by incorrect dosing of the compound or incompatible vehicle formulation. Further studies will be required to test these possibilities.

An alternative explanation is that the mechanism of protective actions of tegaserod are not due to activation of mucosal 5-HT₄ receptors. If this were the case, a luminally restricted 5-HT₄ agonist would be ineffective. It is unknown if epithelial 5-HT₄ receptors are located on the apical or basal side of intestinal epithelial cells. If the receptor is located on the basal side of epithelial cells, an agonist would have to be present in the lamina propria to stimulate receptor actions. This would require a mechanism to transport a luminally delivered compound from the lumen into the lamia propria. Under normal conditions, transport mechanisms are predominately expressed in
the small intestine, not colonic epithelial cells. However, the transporter protein hPept1 is aberrantly expressed in colonic epithelial cells of UC and CD patients, and have a role in transporting bacterial di- and tri-peptides across the epithelial barrier (Merlin et al., 2001). Another possible explanation is that tegaserod can diffuse across the compromised epithelial barrier known to occur in experimental colitis, and the luminally restricted 5-HT₄ agonist cannot.

These explanations, while plausible, are unlikely. Previous results from our lab demonstrate that intracolonic administration of tegaserod was significantly more effective than systemic administration (IP) in reducing experimental colitis activity. Additionally, the effect of intracolonic tegaserod was blocked by intraluminal administration of a 5-HT₄ selective antagonist. These results indicate that luminal 5-HT₄ receptor activation is necessary to induce the protective actions, and that it is a 5-HT₄ receptor specific effect. Future investigations involving conditional knockdown of the 5-HT₄ receptor in epithelial cells might be necessary to confirm the involvement of epithelial receptors in the protective actions.

Tegaserod is also a 5-HT₂B receptor antagonist. 5-HT₂B receptors are located on longitudinal and circular gastrointestinal smooth muscle cells and neurons within the myenteric plexus (Engel et al., 1984, Borman et al., 2002). Additionally, tegaserod has similar affinity for the 5-HT₂B receptor as for the 5-HT₄ receptor (Beattie et al., 2004). Therefore, it is possible that any effects of tegaserod on motility could have been complicated by 5-HT₂B antagonism, but it is improbable that 5-HT₂B receptor antagonism
would interfere with protective epithelial actions. Furthermore, it is unknown the affinity of the luminally restricted 5-HT$_4$ agonist for the 5-HT$_{2B}$ receptor.

It is important to note that there were inconsistencies in the model of experimental colitis that was used. We had significant variability in the extent of colitis that was induced, and we were not able to reproduce the protective actions of tegaserod (Figure 1; Supplemental Figures 3 and 4). A possible explanation for the variability in the colitis model is due to the type of DSS used. Previous studies in our lab induced colitis with DSS from MP Biomedicals (Solon, OH; molecular weight: 36,000-50,000), while the current study used DSS from Affymetrix (Cleveland, OH; molecular weight: 40,000-50,000). It is known that dosing and the molecular weight of DSS affect the quality and severity of inflammation (Kitajima et al., 2000). Initial experiments in this study induced colitis with 4% DSS, which resulted in many mice developing severe colitis (histological damage scores >8 at day 5). For later studies, we induced colitis with 3% DSS to stimulate development of a more moderate colitis (histological damage scores 4-8 at day 5). However, even with this reduction in colitis severity, we failed to see a recovery effect of 832Z or tegaserod.

It was surprising that we were unable to recapitulate the effects of tegaserod. This may be attributed to the inconsistencies in the model; therefore, these findings do not overturn the previously reported data by our lab (Spohn et al., 2016).

Lastly, it is plausible that this particular luminally restricted compound, 832Z, does not promote epithelial wound healing. Given that this is the first time 832Z has been tested in vivo, it is possible that we are not seeing effects because this drug does not exert
an effect on the mechanisms addressed in this study. Other research in our lab does
demonstrate a prokinetic effect of 832Z administration in naïve animals, and this effect is
blocked by a 5-HT$_4$ antagonist (data not shown). These results are in line with our
hypothesis and indicate that the compound is active, and stimulates mucosal 5-HT$_4$
receptors when administered by gavage or enema.

While this study revealed no effects of the luminally restricted 5-HT$_4$ agonist
SYR313832Z, there is need for further study to confirm these findings. This study was
complicated by inconsistencies in the animal model and a lack of effect of the positive
control, tegaserod. While it is possible that this compound does not exert protective
actions in colitis, there is not sufficient evidence to make a definitive conclusion.

**Concluding Remarks**

This study tested the effects of a novel therapeutic agent, a luminally restricted 5-
HT$_4$ agonist, in an *in vivo* animal model of colitis. The results show that this novel
compound does not exert protective epithelial actions or prokinetic effects in dextran
sodium sulfate induced colitis. However, further studies need to be done to assess this
novel compound with additional assays to make a definitive conclusion.
VI. Works Cited


Hoffman JM, McKnight ND, Sharkey KA, Mawe GM (2011) The relationship between inflammation-induced neuronal excitability and disrupted motor activity in the


Figure 1
Figure Legend

Figure 1. Results from a 15-day recovery paradigm. Male CD1 mice, 8-10 weeks old.
Vehicle n=5*. 832Z n=8. Tegaserod n=7. Colitis induced with 3% DSS. Enema treatment
with vehicle (1% DMSO/0.9% saline), SYR313832Z (10 mg/kg SYR313832Z, 1%
DMSO/0.9% saline) or tegaserod (1 mg/kg tegaserod, 1% DMSO/0.9% saline). A)
Disease activity index over the course of the paradigm. There were no significant
differences in disease activity index (p=0.1598), however there was a significant effect of
day (p<0.0001) via 2-way ANOVA. B) Disease activity index for day 15. C) Histological
damage scores (p=0.7545 by one-way ANOVA). D) Percent Epithelial cells Ki67+, reported as a ratio of Ki67+ cells:DAPI stained nuclei. Each data point represents one
animal, as an average of 3 crypts. (p=0.06217 by one-way ANOVA). E) Fecal Lipocalin-
2 levels for days 0, 5, 10 and 15. There is no significant effect of treatment (p=0.7123),
but there is a significant effect of day (p=0.038) by two-way ANOVA. F) Bead expulsion
times for Days 0, 5, and 15, reported as percent of day 0 expulsion time. All times are
calculated as the latency from wake to expulsion, and the normalized to the day 0
expulsion time. There was no significant effect of treatment (p=0.4298) or day
(p=0.7280) by two-way ANOVA. *One mouse was euthanized on day 9 due to >30%
weight loss and lethargy as per protocol.
Supplemental Figure 1
Figure Legend

Supplemental Figure 1. Results from a 15-day recovery paradigm. Male CD1 mice, 8-10 weeks old, 5 mice per group. Colitis induced with 4% DSS. Gavage treatment with vehicle (0.5% methylcellulose, 50 mM citrate monohydrate in double distilled water, pH 3.0) or agonist (10 mg/kg SYR3138637, 0.5% methylcellulose, 50 mM citrate monohydrate in double distilled water, pH 3.0). A) Disease activity index over the course of the paradigm showed no significant effect of treatment (p=0.5103), but there was a significant effect of day (p<0.0001) by two-way ANOVA. Mice reached a peak average score of ~7, indicating moderate to severe colitis. B) Histological damage scores showed no significant differences between groups (p=0.7245 by unpaired t-test). C) Bead expulsion times for Days 0, 5, and 14, reported as percent of day 0 expulsion time. All times are calculated as the latency from wake to expulsion, and the normalized to the day 0 expulsion time. Significant effect of treatment by two-way ANOVA (p=.0098). D) Percent Epithelial cells Ki67+, reported as a ratio of Ki67+ cells:DAPI stained nuclei. Each data point represents one animal, as an average of 3 crypts. There were no significant differences between groups (p=0.5644 by unpaired t-test). E) Lcn-2 levels as detected by ELISA showed no significant differences between groups (p=0.5264), but there as a significant effect of day (p=0.0052) by two-way ANOVA. F) Fecal output showed no effect of treatment (p=0.6006), but there was a significant effect of day (p=0.0356) by two-way ANOVA. G) Fecal water content demonstrated to effect of treatment (p=0.6418), but there was a significant effect of day (p<0.0001) by two-way ANOVA.
Supplemental Figure 2
Figure Legend

Supplemental Figure 2. Results from a 15-day recovery paradigm. Male CD1 mice, 8-10 weeks old, 5 mice per group. Colitis induced with 4% DSS. Gavage treatment with vehicle (1% Tween80/Tap water) or agonist (10 mg/kg SYR313832Z, 1% Tween80/Tap water). A) Disease activity index over the 15-day paradigm demonstrated no effect of treatment (p=0.2123), but a significant effect of day (p<0.0001) by two-way ANOVA. B) Histological damage scores demonstrated no significant differences between treatment (p=0.4011) by an unpaired t-test. C) Percent Epithelial cells Ki67+, reported as a ratio of Ki67+ cells: DAPI stained nuclei. Each data point represents one animal, as an average of 3 crypts. There was no significant difference between groups (p=0.1557) by an unpaired t-test.
Supplemental Figure 3
**Figure Legend**

Supplemental Figure 3. Results from a 15-day recovery paradigm. Male CD1 mice, 8-10 weeks old, 5 mice per group. Colitis induced with 4% DSS. Gavage treatment with vehicle (1% Tween80/Tap water), agonist (10 mg/kg SYR313832Z, 1% Tween80/Tap water) or enema treatment with tegaserod (1 mg/kg tegaserod, 1% DMSO/0.9% saline).

A) Disease activity index scores over the course of the paradigm. Tegaserod improved DAI quicker than oral 832Z or vehicle, as seen by significant difference on days 8 and 10 (*p<0.05 between Tegaserod and both vehicle and oral 832Z; ψ p<0.05 between Tegaserod and oral 832Z; analysis by two-way ANOVA with multiple comparisons, Bonferroni corrections). B) Histological damage scores demonstrated no significant differences between treatments at day 15 (p=0.7214) by one-way ANOVA. C) Fecal Lipocalin-2 levels on days 0, 5, 7 and 15 as detected by ELISA demonstrated no effect of treatment (p=0.3208), but a significant effect of day (p=0.0009) by two-way ANOVA. D) Raw bead expulsion times, shown as latency from wake to expulsion in seconds demonstrate no significant effect of treatment (p=0.4642) or day (p=0.9734) by two-way ANOVA.
Supplemental Figure 4
Figure Legend

Supplemental Figure 4. Results from a 15-day recovery paradigm. Male CD1 mice, 8-10 weeks old, 5 mice per group. Colitis induced with 4% DSS. Enema treatment with vehicle (1% DMSO/0.9% saline), SYR313832Z (10 mg/kg or 1 mg/kg SYR313832Z, 1% DMSO/0.9% saline) or tegaserod (1 mg/kg tegaserod, 1% DMSO/0.9% saline). A) Disease activity index scores over the course of the paradigm demonstrated no effect of treatment (p=0.6824), but a significant effect of day (p<0.0001) by two-way ANOVA. B) Histological damage scores demonstrate no effect of treatment (p=0.9594) on day 15 by one-way ANOVA. C) Percent Epithelial cells Ki67+, reported as a ratio of Ki67+ cells:DAPI stained nuclei. Each data point represents one animal, as an average of 3 crypts. There was no significant difference between groups (p=0.1017) by one-way ANOVA. D) Bead expulsion times for Days 0, 5, and 15, reported as percent of day 0 expulsion time. All times are calculated as the latency from wake to expulsion, and the normalized to the day 0 expulsion time. There was no significant effect of treatment (p=0.1692) or day (p=0.1116) by two-way ANOVA.
Supplemental Figure 5
Figure Legend

Supplemental Figure 5. Results from a preliminary experiment inducing colitis with either 3% or 2.5% DSS and collected fecal samples for Lcn-2 ELISA at days 5, 10, 15, 20 and 25. CD1 male mice, aged 8 weeks, 3 mice per group. There was no significant effect of treatment (p=0.4487) or day (p=0.2090) by two-way ANOVA.
CHAPTER III: FINAL CONCLUSIONS AND FUTURE DIRECTIONS

I. Summary and Conclusions

There is a drastic need for novel therapeutic agents for IBD. The current therapies, including anti-inflammatory agents, immunosuppressants, and monoclonal antibodies, do not serve all patient needs. A unique target for treatment in IBD is the epithelial barrier. Compromised barrier function, or “leaky gut”, is a common feature of IBD and may even contribute to the pathogenesis. This study aimed to explore mucosal 5-HT$_4$ receptor activation using a luminally restricted 5-HT$_4$ agonist as a novel therapeutic target for IBD and other functional bowel disorders.

Results from my study reveal that the luminally restricted 5-HT$_4$ agonist failed to exert protective effects in DSS induced colitis. These results were surprising and prompt the use of other paradigms and techniques to fully reveal the effects of this compound.

II. Future Directions

A primary concern of this study was the inconsistencies and variability within the colitis model. It is known that induction of DSS colitis is dependent on both the mouse strain and the molecular weight of DSS used (Kitajima et al., 2000, Chassaing et al., 2014). I think it would be beneficial for future studies to utilize a different mouse strain or DSS from a different company to explore the protective actions of 832Z. C57BL/6 mice are another commonly used strain to study DSS colitis, and I think attempting a recovery paradigm with this strain would be beneficial. Additionally, other labs have shown recovery of fecal lipocalin-2 levels in C57BL/6 mice. Given the lack of return to
baseline of fecal lipocalin-2 levels in the CD-1 mice used in this study, it would be beneficial to utilize a strain where we know that this biomarker can indicate a reduction in inflammation. Furthermore, our lab has demonstrated prokinetic effects of 832Z in naïve C57BL/6 mice, but not CD-1 mice. We initially used CD-1 mice for the colitis studies based on the previous work in our lab showing protective epithelial actions of tegaserod in CD-1 mice (Spohn et al., 2016). However, the CD-1 mice used in this study had hemoccult positive stool at baseline, and sometimes soft stool, indicating a slight dysregulation of epithelial barrier homeostasis prior to induction of colitis. We were unable to identify the cause of these symptoms. C57BL/6 mice concurrently used in our lab did not show the same symptoms. Therefore, I think it would be beneficial to test this same hypothesis using C57BL/6 mice given that they are healthy at baseline and we have seen effects of the compound on gastrointestinal motility. Additionally, I propose using a more sensitive disease activity index rubric for the daily disease scoring. A protocol update for chemically induced models of colitis included a disease activity index rubric with more detailed scoring of stool consistency and fecal blood (see table 3) (Wirtz et al., 2017). Utilization of this more detailed DAI rubric would take away some of the inherent subjectivity of scoring stool consistency.

<table>
<thead>
<tr>
<th>Score</th>
<th>Weight Loss</th>
<th>Stool Consistency</th>
<th>Occult/gross bleeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td>Normal</td>
<td>Negative hemoccult</td>
</tr>
<tr>
<td>1</td>
<td>1-5%</td>
<td>Soft but still formed</td>
<td>Positive hemoccult</td>
</tr>
<tr>
<td>2</td>
<td>5-10%</td>
<td>Soft</td>
<td>Positive hemoccult</td>
</tr>
<tr>
<td>3</td>
<td>10-20%</td>
<td>Very soft; wet</td>
<td>Blood traces in stool</td>
</tr>
<tr>
<td>4</td>
<td>&gt;20%</td>
<td>Watery diarrhea</td>
<td>Gross rectal bleeding</td>
</tr>
</tbody>
</table>

Table 3. Scoring system for disease activity index from Wirtz et al. (2017)
Given the null results of this study in an in vivo model, I also suggest testing the actions of 832Z with in vitro and ex vivo assays that specifically test the effects on barrier function and wound healing. It is known that barrier function is disrupted in colitis and experimental models of colitis (Stein et al., 1998, Turner, 2009). One of the three primary actions of 5-HT₄ agonists identified by our lab is improvement of barrier function, facilitated by improved wound healing in colitis. Wound healing can be tested in vitro using a scratch assay in Caco-2 cells, which specifically measures epithelial migration. Caco-2 cells are a human epithelial adenocarcinoma cell line that are frequently used to assess properties of intestinal epithelial cells in vitro. Previous reports in our lab demonstrate that tegaserod improves closure of the scratch over vehicle control, and that this is blocked by co-administration of a 5-HT₄ selective antagonist (Spohn et al., 2016).

Another important component of wound healing is the rate of apoptosis. Reactive oxygen species caused by oxidative stress are present in colitis and contribute to epithelial apoptosis (Shi et al., 2011, Novak and Mollen, 2015, Spohn et al., 2016). To assess the effect of 832Z on reactive oxygen species induced apoptosis, Caco-2 cells are pretreated with the compound, exposed to H₂O₂, and then the percent of cells undergoing apoptosis is measured. This question could also be answered in vivo by using a colitis prevention paradigm and performing a TUNEL assay on sections of colon after treatment. Barrier function or intestinal permeability can be specifically tested ex vivo or in vitro using Ussing chamber assays or measuring transepithelial resistance of cultured cells, respectively.
This study used one method to assess colonic motility in inflamed mice. There are many other assays, some more sensitive than bead expulsion, that can be utilized. Current data from our lab indicate prokinetic effects with acute treatment of 832Z in naïve mice using measures of whole gastrointestinal transit. Additionally, smaller motor events such as colonic migrating motor complexes and slow wave motor events can be video-captured from ex vivo colon preparations and analyzed to show changes in these more minute phenomena. These ex vivo assays can be performed after administration of compound to the animal, or with application in the ex vivo bath preparation. Lastly, the integrity of the neuromuscular junction can be assessed using intracellular electrophysiology to record junction potentials from longitudinal smooth muscle cells.

In conclusion, there are many other detection measures that can be utilized to assess the effects of the luminally restricted 5-HT₄ agonist 832Z. While my study did not demonstrate any effects of this compound, it was the first study to explore the novel therapeutic mechanism of luminally restricted compounds in a model of experimental colitis. Additionally, this was the first study to my knowledge assessing fecal lipocalin-2 levels in CD-1 mice in response to a therapeutic treatment in a model of colitis. These results will inform future studies into the protective epithelial actions of this and future luminally restricted 5-HT₄ agonists.
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