COLONIC ORGANOIDS AND METHODS OF MAKING AND USING SAME

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 62/429,948 filed December 5, 2016, which is incorporated herein by reference it its entirety for all purposes.

BACKGROUND

[0002] While the generation of gastric and small intestinal organoids from pluripotent stem cells (PSCs) has revolutionized the study of human gastrointestinal (GI) development and disease, the efforts to generate large intestinal organoids have lagged behind, in part due to the lack of a robust understanding of posterior gut tube development.

BRIEF SUMMARY

[0003] Disclosed herein are methods for the *in vitro* differentiation of a precursor cell into definitive endoderm, which may further be differentiated into a human colonic organoid (HCO), via modulation of signaling pathways. Further disclosed are HCOs and methods of using HCOs, which may be used, for example, for the HCOs may be used to determine the efficacy and/or toxicity of a potential therapeutic agent for a disease selected from colitis, colon cancer, polyposis syndromes, and/or irritable bowel syndrome.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] This application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0005] Those of skill in the art will understand that the drawings, described below, are for illustrative purposes only. The drawings are not intended to limit the scope of the present teachings in any way.

[0006] FIG 1. Bmp signaling regulates *Satb2* expression in mouse and frog embryos. (A) Whole-mount pSmad158 (red) and Foxa2 (green) staining of e8.5 mouse embryo showing nuclear staining around the developing hindgut (n=6). (B) Inset of optical slices from boxed region in (A) showing pSmad1/5/8 staining in the hindgut mesoderm and endoderm (D, dorsal; V, ventral). (C) Schematic of mouse embryo isolated at the headfold stage and cultured for 2 days +/- Bmp inhibition with DMH-1. (D,E) Whole-mount pSmad1/5/8 (red) and Foxa2 (green) staining of DMSO (0) and DMH-1 (E) treated embryos after 48 hours of culture. (F) Quantification of pSmadl/5/8 and pSmad2/3 staining in relative to Cdx2 in embryos cultured in DMSO or DMH-1 (n=3 embryos per condition). (G-J) Whole-mount immunostaining of Cdx2 (green), Satb2 (red) and Foxa2 (white) of mouse embryos (n=6 for each condition) following 2 days of culture in DMSO (G,H) or DMH-1 (I,J). Arrows in H-J point to the approximate location of the yolk stalk (BA1, first brachial arch). (K) Quantification of *Satb2* expression in mouse embryos treated with DMSO or DMH-1. (L) Schematic of Bmp inhibition in Xenopus tropicalis embryos. *In situ* hybridization of Satb2 in Xenopus tropicalis embryos treated with DMSO (M) or DMH-1 (R). The white dotted line in (M) and (R) depict the plane of section used subsequent analysis. Mx and md= maxillary and mandibular processes of first brachial arch. Cba= Caudal brachial arches. Immunofluorescence of Satb2 (red), pSmad1/5/8 (green), DAPI (blue), and color merged images from Xenopus tropicalis embryos treated with DMSO (N-Q) or DMH-1 (S-V). Scale bars for = 100 μm in G-H and 50 μm in all other panels. **p < 0.01 and ***p 0.001 for 2 tailed t-test.

[0007] FIG 2. BMP2 induces SATB2 and a posterior HOX code in human gut tube spheroids. (A) Schematic of gut tube spheroid patterning protocol. (B-D) BMP signaling levels as measured by pSMAD1/5/8 (red) staining of spheroids treated with NOGGIN (B), no treatment (C) and BMP2 (D) for 12 hours. (E) pSmadl/5/8 staining

of adult mouse colon showing increased BMP signaling at to the top of crypts. (F-H) SATB2 expression in spheroids treated with NOGGIN (F), no treatment (G) and BMP2 (H) for 72 hours. (I) Quantification of the percentage of SATB2+ CDH1+ epithelium following patterning. (J) Principal component analysis of nascent spheroids and spheroids after 3 days of patterning. (K) Gene ontology analysis of differentially expressed genes between BMP vs NOG treated spheroids. (L) Graph of TPM (Transcripts per million) values of spheroids before and after patterning. Samples analyzed were spheroids before patterning (n=2), and NOGGIN, Control and BMP2 treated spheroids 3 days after patterning (n=4 for each group). For quantification in I, 20 organoids from at least 3 experiments were examined. Error bars represent SD. Scale bars = 50 microns. ****p s 0.0001 determined by 2 tailed t-test.

[0008] FIG 3. Regional patterning is maintained in human intestinal organoids following prolonged in vitro culture. (A-D) Whole-mount immunofluorescence and QPCR analysis with the proximal marker ONECUTI (green) of 28-day old organoids that resulted from the initial 3 day treatment of spheroids with NOGGIN, control, or BMP2. Staining with CDX2 (red) and DAPI (blue) were also used to detect the epithelium and mesenchyme. (E-H) Expression of the posterior marker SATB2 (red) detected by IF and by QPCR. (I-L) Analysis of the pan-goblet cell marker MUC2 (red) by IF and by QPCR. (M-P) Analysis of the colon-specific goblet cell marker MUC5B (red) by IF. The number of MUC5B+ cells was quantified in (P). (Q-S) Analysis of patterning markers in isolated mesenchyme cultures relative to whole organoids. QPCR analysis of CDH1 (Q), the proximal HOX gene HOXD3 (R), and the distal HOX gene HOXA13 (S) in whole organoids and in mesenchyme cultures derived from NOGGIN, control, or BMP2 treated organoids. CDH1 was only observed in whole organoids that contained epithelial cells. Error bars represent SEM. For IF minimum of 10 organoids from at least 3 different experiments were examined for each condition. For QPCR a minimum of 5 biological replicates from 2 separate experiments were examined. Scale bars = 100 microns. **p 5 0.01 and ****p 5 0.0001 determined by 2 tailed t-test.

[0009] FIG 4. HCOs but not HIOs gave rise to colon-specific enteroendocrine cells in response to expression of the proendocrine transcription factor NEUROGENIN 3. (A-B) Schematic of the doxycycline inducible NEUROG3 lentiviral construct used to generate the IPSC72.3 inducible NEUROG3 line, and the doxycycline induction protocol. Whole-mount staining with Chromagranin A (green), CDX2 (red) and INSL5 (white) of 35 day old organoids patterned with NOGGIN (C,F), untreated (D,G) or BMP (E,H). (C-E) Untreated organoids (-Dox) and (F-H) organoids with expressed NEUROG3 (+Dox). Insets in E and H show a magnified view of INSL5 staining. (I, J) QPCR analysis of NEUROG3 induction of enteroendocrine cells in HIOs and HCOs as measured by CHGA (I) and for INSL5 (J) expression. Data is representative of 2 different experiments with NOGGIN (n=3), Control (n=3) or BMP (n=6) treated organoids. Error bars represent SEM. Scale bars = 50 microns. *$p < 0.05$ determined by 2 tailed t-test.

[0010] FIG 5. HIOs and HCOs maintained regional identity following transplantation in vivo. (A-E) H&E staining of biopsies from human jejunum and colon and of NOGGIN-derived HIOs, control HIOs, and BMP2-derived HCOs that were transplanted underneath the mouse kidney capsule and grown for 8-10 weeks in vivo. The samples of the same conditions were stained with the proximal intestinal marker GATA4 (F-J), the distal intestinal marker SATB2 (K-0), the Paneth cell marker DEFAS (P-T), and the colon-specific goblet cell marker MUC5B (U-Y). Note that although GATA4 and SATB2 double staining was done in different channels but on the same slides for panels (F-0), they are shown as individual pseudo-colored (red) images. For human biopsies n=2. For transplanted NOGGIN treated organoids n=12, for control organoids n=7, and for BMP2 treated organoids n=16. Scale bars= 50 pm.

[0011] FIG 6. *In vivo* grown organoids express region-specific hormones. Analysis of expression of the regionally expressed hormones (A-D) Ghrelin (GHRL), Motilin (MLN), (E-H) GIP, (I-L) GLP-1, (M-P) PYY and (Q-T) INSL5 in HIOs and HCOs grown for 8-10 weeks underneath the mouse kidney capsule. The proximally enriched hormones GHRL, GIP and MLN were enriched in NOGGIN and control HIOs

(A-H). The distally enriched hormones GLP-1 and PYY were enriched in BMP2-derived HCOs (1-0). The colon specific hormone INSL5 was only present in HCO (Q-T). Data is representative of a minimum of 5 transplanted organoids per condition. Insets in (A) and (B) show GHRL and MLN double positive cells. (D, H, L, P, T) FPKM values for GHRL, MLN, GIP, GLP1, PYY, and INSL5 are from RNA-seq data. FPKM values represent 3 biological replicates per condition. Scale bars= 30 microns.

[0012] FIG 7. Global transcriptional analysis of HIOs and HCOs and comparison with human small intestine and colon. (A) Principal component analysis human adult and fetal small intestine and colon compared with transplanted HIOs and HCOs. (B) Hypergeometric means test comparing human adult small intestine with HIOs and human adult colon with HCOs. (C) 4-way scatter plot comparing transcripts that were differentially expressed in human small intestine and colon compared to HIOs and HCOs.

[0013] FIG 8. Gata4 and Satb2 mark discreet regional boundaries during development of the small and large intestines. (A) Whole-mount staining of Gata4 (green) and Satb2 (red) in an e9.5 mouse embryo showing expression boundary at the yolk stalk (n=9). (B) Model depicting Gata4 and Satb2 expression domains el 1.5 intestine showing a transitional zone of low Gata4 and low Satb2 expression. (C¬E) Whole-mount staining of Gata4 and Satb2 in an e11.5 mouse embryo showing posterior boundary of Gata4 and anterior boundary of Satb2 at the yolk stalk (n=3). (F-H) Whole-mount staining of Satb2 and Foxa2 in an e12.5 mouse embryo showing that the anterior boundary of Satb2 expression is maintained (n=3). (I) Whole-mount staining of Gata4 and Satb2 in proximal intestine isolated from an e16.5 mouse embryo (n=6). (J) Whole-mount staining of Gata4 and Satb2 in distal small intestine and large intestine isolated from an e16.5 mouse embryo (n=6). Staining of GATA4 and SATB2 in section of (K) human jejunum (n=2) and (L) colon (n=2). Scale bars = 50 µm (B-D) and 100 1Am (E-M). Dotted lines in (C) and (F) mark the approximate location of the umbilicus. Abbreviations: ys, yolk stalk; cb, cecal bud; tz, transition zone; mx, maxilliary; and md, mandibular portion of first brachial arch; ti, terminal ileum; icj, ileocecal junction.

[0014] FIG 9. SATB2 is expressed in GATA4 negative human small and large intestine. SATB2 staining in human adult duodenum, small intestine, appendix, colon and rectum showing that SATB2 expression is present in distal small intestine and the entire large intestine. Analysis of GATA4 and SATB2 from published RNA-seq data from human adult and fetal intestinal samples. Samples plotted include human adult duodenum (HuSI_Duo_A), human adult small intestine distal to duodenum (HuSI_Dist_A), human adult colon (HuColon_A) and human fetal small intestine (HuSI_F). (C) Analysis of GATA4 and SATB2 expression from microarray data generated by Wang et al. 2015 on fetal intestinal stem cells from duodenum (Duo), jejunum (Jej), ileum (Ile), ascending colon (AC), transverse colon (TC) and Descending colon grown in Air Liquid Interface (ALI). r2 values were determined using CORREL function in Excel.

[0015] FIG 10. BMP mediates SHH activation of posterior HOX genes. (A) Previous model of SHH-mediated activation of posterior HOX genes. (B) New model of SHH mediated activation of posterior HOX genes and BMP-mediated activation of endoderm HOX genes. (C) QPCR analysis of HOX factors following treatment with NOGGIN, control, Smoothened agonist (SAG), or BMP2. (D) Model of BMP4 dependent activation of HOX13 genes induced by SAG. (E) QPCR analysis of HOXA13 in control, 5μM SAG, 5μM SAG + NOG and BMP2 treated organoids after 3 days. (F) Model of SHH independent activation of HOX13 genes induced by exogenous recombinant human BMP2. (G) QPCR analysis of HOXA13 in control, BMP, and BMP + Cyclopamine treated organoids after 3 days (n=6 per condition).

[0016] FIG 11. Extended in vitro culture allows maturation of goblet cells. (A) Quantitation of the percentage of CDX2+ SATB2+ cells in organoids which were patterned and were then re-patterned. QPCR analysis of HOXB13 (B) and HOXD13 (C) in 28-day old organoids. (D-F) Whole-mount and (G-I) cross section staining with CDH1 (green), CDX2 (red), and MUC2 (white) from 44-day old NOGGIN, Control, and BMP treated organoids. (J-L) Staining of sections from 44-day old BMP2 treated organoids. White arrows points to goblet cells which were in the process of secreting

Mucin 2. For QPCR a minimum of 5 biological replicates from 2 separate experiments were examined. For IF a minimum of 10 organoids per condition were examined. Scale bars= 50 pm.

[0017] FIG 12.BMP patterning of organoids is stable in vitro and in vivo. (A) Efficiency of organoid engraftment of NOGGIN, Control, and BMP patterned organoids. Quantitation of the percentage of GATA4+ CDX2+ cells (B) and SATB2+ CDX2+ cells (C) in transplanted patterned organoids. FPKM values from RNA-seq data for GATA4 (D) SATB2 (E) DEFAS (F) and MUCSB (G) in transplanted organoids. MUC2 (red) staining of (H-I) human jejunum and colon biopsies (n=2 per region) and (J-L) transplanted organoids (n=5 per condition). Scale bars= 50 microns.

[0018] FIG 13. *In vitro* and *in vivo* grown organoids contain intestinal progenitors. Representative whole-mount (A,F,K) and slice section (B,G,L) images of CDH1 and GFP from H9-LGR5-GFP derived organoids treated with NOGGIN, control, or BMP. CDX2 (red) and SOX9 (green) staining on sections from (C-E) NOGGIN, (H-J) control, or (M-O) BMP2 treated organoids. Representative images of CDX2 and LGR5-GFP (P, S,V), CDX2 and SOX9 (Q,T, W), and CDH1 and KI67 (R,U,X) stained in vivo organoids derived from H9-LGR5-GFP organoids treated with NOGGIN, control, or BMP. (Y-A') Stereomicrographs showing enteroids derived from NOGGIN, control or BMP transplants respectively. (B'-D') QPCR analysis of proximal and distal genes in control enteroids (>100 pooled enteroids from 2 transplants) and BMP2 treated colonoids (>50 colonoids from 1 transplant). Scale bars= 50 μm.

[0019] FIG 14. Ribosome and immune cell signatures are differentially expressed between transplanted organoids and primary human tissues. (A) Principal component analysis of patterned transplanted organoids and human adult and fetal small intestine and colon. (B) Gene ontology analysis of genes upregulated in transplants versus human primary tissues. (C) Gene ontology analysis of genes upregulated in human primary tissues versus transplants.

[0020] FIG 15. (A) Wholemount immunofluorescence staining of HCOs after 15 days of growth in Matrigel. HCO cultures were stained for the endothelial marker CD31 (green) and the hindgut epithelium marker CDX2 (red). Cultures were also stained for the hematopoietic cell marker PU.1 (red right panel). (B) Schematic of hematopoietic progenitor assays. Cells were collected from HCOs, centrifuged and either stained using Giemsa Wright Stain or plated in Methocult media to assay for hematopoietic cell differentiation. (C) Representative images of Giemsa Wright stained cells with morphologies consistent with differentiation into Macrophages, Neutrophils, Basophils and Eosinophils. (D) Representative images of colonies formed after 14 days in Methocult. Erythrocyte, macrophage and granulocyte colonies were present in cells derived from HCOs but not those derived from NOGGIN treated HIOs.

[0021] FIG 16. (A) Immunofluorescence staining of a human colon biopsy or an HCO grown for 28 days in Matrigel. Staining was done for CD68 a marker of macrophages. (B) Plots of CYTOF analysis of CD14 and CD16 in HIOs and HCOs. A small percentage of CD14+/CD16+ cells are present in HCOs (blue square) but not HIOs. Additionally, CD16 single positive cells were present in HCOs suggesting monocytes are present within the culture. (C) Luminex array analysis of supernatant collected from 14 and 28-day old HIOs and HCOs. IL6 and IL8 were detected in 28-day old HCOs (BMP) but not HIOs. (D) Luminex array analysis of supernatant collected from 14 and 28-day old HIOs and HCOs. The macrophage specific cytokines MIP1A and MIP1B were detected in 14 and 28-day old HCOs (BMP) but not in 14 or 28-day old HIOs.

Detailed Description

[0022] Definitions.

[0023] Unless otherwise noted, terms are to be understood according to conventional usage by those of ordinary skill in the relevant art.

[0024] The term "about" or "approximately" means within an acceptable error range for the particular value as determined by one of ordinary skill in the art, which will depend in part on how the value is measured or determined, e.g., the limitations of the measurement system. For example, "about" can mean within 1 or more than 1 standard deviation, per the practice in the art. Alternatively, "about" can mean a range of up to 20%, or up to 10%, or up to 5%, or up to 1% of a given value. Alternatively, particularly with respect to biological systems or processes, the term can mean within an order of magnitude, preferably within 5-fold, and more preferably within 2-fold, of a value. Where particular values are described in the application and claims, unless otherwise stated the term "about" meaning within an acceptable error range for the particular value should be assumed.

[0025] As used herein, the term "totipotent stem cells" (also known as omnipotent stem cells) are stem cells that can differentiate into embryonic and extra-embryonic cell types. Such cells can construct a complete, viable, organism. These cells are produced from the fusion of an egg and sperm cell. Cells produced by the first few divisions of the fertilized egg are also totipotent.

[0026] As used herein, the term "pluripotent stem cells (PSCs)," also commonly known as PS cells, encompasses any cells that can differentiate into nearly all cells, i.e., cells derived from any of the three germ layers (germinal epithelium), including endoderm (interior stomach lining, gastrointestinal tract, the lungs), mesoderm (muscle, bone, blood, urogenital), and ectoderm (epidermal tissues and nervous system). PSCs can be the descendants of totipotent cells, derived from embryonic stem cells (including embryonic germ cells) or obtained through induction of a non-pluripotent cell, such as an adult somatic cell, by forcing the expression of certain genes.

[0027] As used herein, the term "induced pluripotent stem cells (iPSCs)," also commonly abbreviated as iPS cells, refers to a type of pluripotent stem cells artificially derived from a normally non-pluripotent cell, such as an adult somatic cell, by inducing a "forced" expression of certain genes.

[0028] As used herein, the term "embryonic stem cells (ESCs)," also commonly abbreviated as ES cells, refers to cells that are pluripotent and derived from the inner cell mass of the blastocyst, an early-stage embryo. For purpose of the present invention, the term "ESCs" is used broadly sometimes to encompass the embryonic germ cells as well.

[0029] As used herein, the term "precursor cell" encompasses any cells that can be used in methods described herein, through which one or more precursor cells acquire the ability to renew itself or differentiate into one or more specialized cell types. In some aspects, a precursor cell is pluripotent or has the capacity to becoming pluripotent. In some aspects, the precursor cells are subjected to the treatment of external factors (e.g., growth factors) to acquire pluripotency. In some aspects, a precursor cell can be a totipotent (or omnipotent) stem cell; a pluripotent stem cell (induced or non-induced); a multipotent stem cell; an oligopotent stem cells and a unipotent stem cell. In some aspects, a precursor cell can be from an embryo, an infant, a child, or an adult. In some aspects, a precursor cell can be a somatic cell subject to treatment such that pluripotency is conferred via genetic manipulation or protein/peptide treatment.

[0030] In developmental biology, cellular differentiation is the process by which a less specialized cell becomes a more specialized cell type. As used herein, the term "directed differentiation" describes a process through which a less specialized cell becomes a particular specialized target cell type. The particularity of the specialized target cell type can be determined by any applicable methods that can be used to define or alter the destiny of the initial cell. Exemplary methods include but are not limited to genetic manipulation, chemical treatment, protein treatment, and nucleic acid treatment.

[0031] As used herein, the term "cellular constituents" are individual genes, proteins, mRNA expressing genes, and/or any other variable cellular component or protein activities such as the degree of protein modification (e.g., phosphorylation), for example, that is typically measured in biological experiments (e.g., by microarray or immunohistochemistry) by those skilled in the art. Significant discoveries relating to

the complex networks of biochemical processes underlying living systems, common human diseases, and gene discovery and structure determination can now be attributed to the application of cellular constituent abundance data as part of the research process. Cellular constituent abundance data can help to identify biomarkers, discriminate disease subtypes and identify mechanisms of toxicity.

[0032] As described herein, methods and systems are established using a temporal series of growth factor manipulations to mimic embryonic intestinal development in culture. In particular, methods and systems are established to direct *in vitro* differentiation of PSCs, both human embryonic stem cells (hESC) and induced pluripotent stem cells (iPSC), into intestinal tissue

[0033] The generation of gastric and small intestinal organoids from pluripotent stem cells (PSCs) has revolutionized the study human gastrointestinal (GI) development and disease. However, efforts to generate large intestinal organoids have lagged behind, in part due to a robust molecular understanding of posterior gut tube development. Here, Applicant has found that the intestinal epithelium posterior to the umbilical cord expresses Satb2 throughout development and postnatally. Applicant has further found that BMP signaling establishes the Satb2+ domain in frog and mouse embryos, and that brief activation of BMP signaling was sufficient to activate a posterior HOX code and direct human PSC-derived gut tube cultures into colonic organoids (HCOs). HCOs grown *in vitro* had a marker profile and unique cell types consistent with colonic identity. Following transplantation into mice, HCOs underwent morphogenesis and maturation forming tissue with molecular, cellular and morphologic properties of the human colon. The disclosed colonic organoids may be used in future studies of colitis and colon cancer.

[0034] In one aspect, a method of inducing formation of a human colon organoid is disclosed. The method may comprise the steps of (a) contacting a definitive endoderm (DE) with an FGF signaling pathway activator and a WNT signaling pathway activator (for example, CHIRON/GSK2 inhibitor) for a period of time sufficient for said DE to form a mid-hindgut spheroid, and (b) contacting the mid-hindgut spheroid

of step (a) with a BMP activator and an EGF signaling pathway activator for a period of time sufficient to form said human colon organoid, wherein said human colon organoid expresses SATB2.

[0035] In one aspect, the DE may be derived from a precursor cell selected from an embryonic stem cell, an embryonic germ cell, an induced pluripotent stem cell, a mesoderm cell, a definitive endoderm cell, a posterior endoderm cell, a hindgut cell or combinations thereof.

[0036] In one aspect, the FGF signaling pathway activator may be selected from a small molecule or protein FGF signaling pathway activator, FGF1, FGF2, FGF3, FGF4, FGF10, FGF11, FGF12, FGF13, FGF14, FGF15, FGF16, FGF17, FGF18, FGF19, FGF20, FGF21, FGF22, FGF23, or combinations thereof. The WNT signaling pathway activator may be selected from a small molecule or protein Wnt signaling pathway activator, preferably Lithium Chloride; 2-amino-4,6-disubstituted pyrimidine (hetero) arylpyrimidines; IQ1; QS11; NSC668036; DCA beta-catenin; 2-amino-4-[3,4-(methylenedioxy)-benzyl-amino]-6-(3-methoxyphenyl) pyrimidine, Wnt1, Wnt2, Wnt2b, Wnt3, Wnt3a, Wnt4, Wnt5a, Wnt5b, Wnt6, Wnt7a, Wnt7b, Wnt8a, Wnt8b, Wnt9a, Wnt9b, Wnt10a, Wnt10b, Wnt11, Wnt16, a GSK3 inhibitor, preferably CHIRON, or combinations thereof. In one aspect, the BMP activator may be selected from BMP2, BMP4, BMP7, BMP9, small molecules that activates the BMP pathway, proteins that activate the BMP pathway, and may include the following: Noggin, Dorsomorphin, LDN189, DMH-1, ventromophins, and combinations thereof.

[0037] In one aspect, the period of time sufficient for said DE to form a mid-hindgut spheroid may be determined by expression of CDX2 by said mid-hindgut spheroid of step (a). Such measurement is within the ability of one of ordinary skill in the art using routine methods.

[0038] In one aspect, the period of time sufficient for the mid-hindgut spheroid to form a human colon organoid is determined by expression of SATB2 and CDX2 by a cell of said human colon organoid, wherein when SATB2 and CDX2 is

expressed, the mid-hindgut spheroid has formed a human colon organoid. Such measurement may be used in lieu of a temporal measurement, in that expression of the genes listed above indicates that steps (a) and (b) have been carried out for a sufficient duration of time.

[0039] In one aspect, an HCO obtained according to the methods described herein are disclosed. The HCOs of the instant invention may be characterized in a variety of different ways. In one aspect, the HCO may be characterized by the presence of colonic enteroendocrine cells (EEC). In one aspect, the HCO may be characterized by the presence of crypts and is substantially free of villi. In one aspect, the HCO may be characterized by the presence of colon-specific goblet cells. In one aspect, the HCO may be characterized by being substantially free of Paneth cells. In one aspect, the HCO may be characterized by the ability to secrete colon-specific hormone INSL5. The intestinal organoid may be free of one or more of an immune function, innervation, blood vessels, villi, and Paneth cells.

[0040] In one aspect, a method of forming colonic tissue is disclosed, wherein the HCO of the described invention may be engrafted under a kidney capsule of a mammal, preferably a rodent, preferably an immunocompromised rodent, preferably an immunocompromised mouse.

[0041] In one aspect, the HCOs disclosed herein may be used to determine the efficacy and/or toxicity of a potential therapeutic agent for a disease selected from colitis, colon cancer, polyposis syndromes, and/or irritable bowel syndrome. The method may comprise the step of contacting a potential therapeutic agent with an HCO as described herein, for a period of time sufficient to determine the efficacy and/or toxicity of said potential therapeutic agent.

[0042] In one aspect, an intestinal colonoid derived from the HCO of any preceding claim is contemplated.

[0043] In some aspects, stem cells that are pluripotent or can be induced to become pluripotent may be used. In some aspects, pluripotent stem cells are derived

from embryonic stem cells, which are in turn derived from totipotent cells of the early mammalian embryo and are capable of unlimited, undifferentiated proliferation *in vitro*. Embryonic stem cells are pluripotent stem cells derived from the inner cell mass of the blastocyst, an early-stage embryo. Methods for deriving embryonic stem cells from blastocytes are well known in the art. For example, three cell lines (H1, H13, and H14) had a normal XY karyotype, and two cell lines (H7 and H9) had a normal XX karyotype. Human embryonic stem cells H9 (H9-hESCs) are used in the exemplary aspects described in the present application, but it would be understood by one of skill in the art that the methods and systems described herein are applicable to any stem cells.

[0044] Additional stem cells that can be used in aspects in accordance with the present invention include but are not limited to those provided by or described in the database hosted by the National Stem Cell Bank (NSCB), Human Embryonic Stem Cell Research Center at the University of California, San Francisco (UCSF); WISC cell Bank at the Wi Cell Research Institute; the University of Wisconsin Stem Cell and Regenerative Medicine Center (UW-SCRMC); Novocell, Inc. (San Diego, California); Cellartis AB (Göteborg, Sweden); ES Cell International Pte Ltd (Singapore); Technion at the Israel Institute of Technology (Haifa, Israel); and the Stem Cell Database hosted by Princeton University and the University of Pennsylvania. Exemplary embryonic stem cells that can be used in aspects in accordance with the present invention include but are not limited to SA01 (SA001); SA02 (SA002); ES01 (HES-1); ES02 (HES-2); ES03 (HES-3); ES04 (HES-4); ES05 (HES-5); ES06 (HES-6); BG01 (BGN-01); BG02 (BGN-02); BG03 (BGN-03); TE03 (I3); TE04 (I4); TE06 (I6); UC01 (HSF1); UC06 (HSF6); WA01 (H1); WA07 (H7); WA09 (H9); WA13 (H13); WA14 (H14).

[0045] In some aspects, the stem cells are further modified to incorporate additional properties. Exemplary modified cell lines include but not limited to H1 OCT4-EGFP; H9 Cre-LoxP; H9 hNanog-pGZ; H9 hOct4-pGZ; H9 inGFPhES; and H9 Syn-GFP.

[0046] More details on embryonic stem cells can be found in, for example, Thomson *et al.*, 1998, "Embryonic Stem Cell Lines Derived from Human Blastocysts,"

Science 282 (5391):1145-1147; Andrews *et al.*, 2005, "Embryonic stem (ES) cells and embryonal carcinoma (EC) cells: opposite sides of the same coin," *Biochem Soc Trans* 33:1526–1530; Martin 1980, "Teratocarcinomas and mammalian embryogenesis,". *Science* 209 (4458):768–776; Evans and Kaufman, 1981, "Establishment in culture of pluripotent cells from mouse embryos," *Nature* 292(5819): 154–156; Klimanskaya et al., 2005, "Human embryonic stem cells derived without feeder cells," *Lancet* 365 (9471): 1636–1641; each of which is hereby incorporated herein in its entirety.

[0047] Alternatively, pluripotent stem cells can be derived from embryonic germ cells (EGCs), which are the cells that give rise to the gametes of organisms that reproduce sexually. EGCs are derived from primordial germ cells found in the gonadal ridge of a late embryo, have many of the properties of embryonic stem cells. The primordial germ cells in an embryo develop into stem cells that in an adult generate the reproductive gametes (sperm or eggs). In mice and humans, it is possible to grow embryonic germ cells in tissue culture under appropriate conditions. Both EGCs and ESCs are pluripotent. For purpose of the present invention, the term "ESCs" is used broadly sometimes to encompass EGCs.

[0048] Induced Pluripotent Stem Cells (iPSCs)

[0049] In some aspects, iPSCs are derived by transfection of certain stem cell-associated genes into non-pluripotent cells, such as adult fibroblasts. Transfection may be achieved through viral vectors, such as retroviruses. Transfected genes include the master transcriptional regulators Oct-3/4 (Pouf51) and Sox2, although it is suggested that other genes enhance the efficiency of induction. After 3-4 weeks, small numbers of transfected cells begin to become morphologically and biochemically similar to pluripotent stem cells, and are typically isolated through morphological selection, doubling time, or through a reporter gene and antibiotic selection. As used herein, iPSCs include but are not limited to first generation iPSCs, second generation iPSCs in mice, and human induced pluripotent stem cells.

[0050] In some aspects, non-viral based technologies may be employed to generate iPSCs. In some aspects, an adenovirus can be used to transport the requisite four genes into the DNA of skin and liver cells of mice, resulting in cells identical to embryonic stem cells. Since the adenovirus does not combine any of its own genes with the targeted host, the danger of creating tumors is eliminated. In some aspects, reprogramming can be accomplished via plasmid without any virus transfection system at all, although at very low efficiencies. In other aspects, direct delivery of proteins is used to generate iPSCs, thus eliminating the need for viruses or genetic modification. In some embodiment, generation of mouse iPSCs is possible using a similar methodology: a repeated treatment of the cells with certain proteins channeled into the cells via poly-arginine anchors was sufficient to induce pluripotency. In some aspects, the expression of pluripotency induction genes can also be increased by treating somatic cells with FGF2 under low oxygen conditions.

[0051] More details on embryonic stem cells can be found in, for example, Kaji *et al.*, 2009, "Virus free induction of pluripotency and subsequent excision of reprogramming factors," *Nature* 458:771-775; Woltjen *et al.*, 2009, "*piggyBac* transposition reprograms fibroblasts to induced pluripotent stem cells," *Nature* 458:766-770; Okita *et al.*, 2008, "Generation of Mouse Induced Pluripotent Stem Cells Without Viral Vectors," *Science* 322(5903):949-953; Stadtfeld *et al.*, 2008, "Induced Pluripotent Stem Cells Generated without Viral Integration," *Science* 322(5903):945-949; and Zhou *et al.*, 2009, "Generation of Induced Pluripotent Stem Cells Using Recombinant Proteins," *Cell Stem Cell* 4(5):381-384; each of which is hereby incorporated herein in its entirety.

[0052] In some aspects, exemplary iPS cell lines include but not limited to iPS-DF19-9; iPS-DF19-9; iPS-DF4-3; iPS-DF6-9; iPS(Foreskin); iPS(IMR90); and iPS(IMR90).

[0053] DEFINITIVE ENDODERM

[0054] The HCOs of the instant disclosure may be derived from a simple sheet of cells called the definitive endoderm (DE). Methods for deriving definitive endoderm from precursor cells are well known in the art, as taught by D'Armour et al. 2005 and Spence et al. The anterior DE forms the foregut and its associated organs including the liver and pancreas and the posterior DE forms the midgut and hindgut, which forms the small and large intestines and parts of the genitourinary system. Studies using mouse, chick and frog embryos suggest that establishing the anterior-posterior pattern in DE at the gastrula stage is a prerequisite for subsequent foregut and hindgut development. The Wnt and FGF signaling pathways are believed to be critical for this process and act to promote posterior endoderm and hindgut fate and suppress anterior endoderm and foregut fate. The simple cuboidal epithelium of the hindgut first develops into a pseudostratified columnar epithelium, then into villi containing a polarized columnar epithelium and a proliferative zone at the base of the villi, which corresponds with the presumptive progenitor domain.

[0055] Applicant describes herein a robust and efficient process to direct the differentiation of DE into intestinal tissue, in particular human colon tissue, *in vitro*. Directed differentiation may be achieved by selectively activating certain signaling pathways in the iPSCs and/or DE cells.

[0056] Additional details of pathways relating to intestinal development in general are found in, for example, Sancho *et al.*, 2004, "Signaling Pathways in Intestinal Development and Cancer," *Annual Review of Cell and Developmental Biology* 20:695-723; Logan and Nusse, 2004, "The Wnt Signaling Pathway in Development and Disease," *Annual Review of Cell and Developmental Biology* 20:781-810; Taipale1 and Beachy1, 2001, "The Hedgehog and Wnt signalling pathways in cancer," *Nature* 411:349-354; Gregorieff and Clevers, 2005, "Wnt signaling in the intestinal epithelium: from endoderm to cancer," *Genes & Dev.* 19: 877-890; each of which is hereby incorporated by reference herein in its entirety. More details on the functions of signaling pathways relating to DE development can be found in, for example, Zorn and

Wells, 2009, "Vertebrate endoderm development and organ formation," *Annu Rev Cell Dev Biol* 25:221-251; Dessimoz *et al.*, 2006, "FGF signaling is necessary for establishing gut tube domains along the anterior-posterior axis *in vivo*," *Mech Dev* 123:42–55; McLin *et al.*, 2007, "Repression of Wnt/{beta}-catenin signaling in the anterior endoderm is essential for liver and pancreas development. Development," 134:2207–2217; Wells and Melton, 2000, *Development* 127:1563-1572; de Santa Barbara *et al.*, 2003, "Development and differentiation of the intestinal epithelium," *Cell Mol Life Sci* 60(7): 1322-1332; each of which is hereby incorporated herein in its entirety.

[0057] Any methods for producing definitive endoderm from pluripotent cells (*e.g.*, iPSCs or ESCs) are applicable to the methods described herein. In some aspects, pluripotent cells are derived from a morula. In some aspects, pluripotent stem cells are stem cells. Stem cells used in these methods can include, but are not limited to, embryonic stem cells. Embryonic stem cells can be derived from the embryonic inner cell mass or from the embryonic gonadal ridges. Embryonic stem cells or germ cells can originate from a variety of animal species including, but not limited to, various mammalian species including humans. In some aspects, human embryonic stem cells are used to produce definitive endoderm. In some aspects, human embryonic germ cells are used to produce definitive endoderm. In some aspects, iPSCs are used to produce definitive endoderm.

[0058] In some aspects, one or more growth factors are used in the differentiation process from pluripotent stem cells to DE cells. The one or more growth factors used in the differentiation process can include growth factors from the TGF-beta superfamily. In such aspects, the one or more growth factors may comprise the Nodal/Activin and/or the BMP subgroups of the TGF-beta superfamily of growth factors. In some aspects, the one or more growth factors are selected from the group consisting of Nodal, Activin A, Activin B, BMP4, Wnt3a or combinations of any of these growth factors. In some aspects, the embryonic stem cells or germ cells and iPSCs are treated with the one or more growth factors for 6 or more hours; 12 or more hours;

18 or more hours; 24 or more hours; 36 or more hours; 48 or more hours; 60 or more hours; 72 or more hours; 84 or more hours; 96 or more hours; 120 or more hours; 150 or more hours; 180 or more hours; or 240 or more hours. In some aspects, the embryonic stem cells or germ cells and iPSCs are treated with the one or more growth factors at a concentration of 10 ng/ml or higher; 20 ng/ml or higher; 50 ng/ml or higher; 75 ng/ml or higher; 100 ng/ml or higher; 120 ng/ml or higher; 150 ng/ml or higher; 200 ng/ml or higher; 500 ng/ml or higher; 1,000 ng/ml or higher; 1,200 ng/ml or higher; 1,500 ng/ml or higher; 2,000 ng/ml or higher; 5,000 ng/ml or higher; 7,000 ng/ml or higher; 10,000 ng/ml or higher; or 15,000 ng/ml or higher. In some aspects, concentration of the growth factor is maintained at a constant level throughout the treatment. In other aspects, concentration of the growth factor is varied during the course of the treatment. In some aspects, the growth factor is suspended in media that include fetal bovine serine (FBS) with varying HyClone concentrations. One of skill in the art would understand that the regimen described herein is applicable to any known growth factors, alone or in combination. When two or more growth factors are used, the concentration of each growth factor may be varied independently.

[0059] In some aspects, populations of cells enriched in definitive endoderm cells are used. In some aspects, the definitive endoderm cells are isolated or substantially purified. In some aspects, the isolated or substantially purified definitive endoderm cells express the SOX17, FOXA2, and/or the CXRC4 marker to a greater extent than the OCT4, AFP, TM, SPARC and/or SOX7 markers. Methods for enriching a cell population with definitive endoderm are also contemplated. In some aspects, definitive endoderm cells can be isolated or substantially purified from a mixed cell population by contacting the cells with a reagent that binds to a molecule that is present on the surface of definitive endoderm cells but which is not present on the surface of other cells in the mixed cell population, and then isolating the cells bound to the reagent. In certain aspects, the cellular constituent that is present on the surface of definitive endoderm cells is CXCR4.

[0060] Additional methods for obtaining or creating DE cells that can be used in the present invention include but are not limited to those described in United States Patent No. 7,510,876 to D'Amour *et al.*; United States Patent No. 7,326,572 to Fisk *et al.*; Kubo1 *et al.*, 2004, "Development of definitive endoderm from embryonic stem cells in culture," Development 131:1651-1662; D'Amour *et al.*, 2005, "Efficient differentiation of human embryonic stem cells to definitive endoderm," Nature Biotechnology 23:1534-1541; and Ang *et al.*, 1993, "The formation and maintenance of the definitive endoderm lineage in the mouse: involvement of HNF3/forkhead proteins," *Development* 119:1301-1315; each of which is hereby incorporated by reference herein in its entirety.

[0061] DEFINITIVE ENDODERM TO MID/HINDGUT SPHEROIDS

[0062] In some aspects, posteriorized endoderm cells of the DE are further developed into one or more specialized cell types. Activin-induced definitive endoderm (DE) can further undergo FGF/Wnt induced posterior endoderm pattering, hindgut specification and morphogenesis, and finally a pro-intestinal culture system that promoted intestinal growth, morphogenesis and cytodifferentiation into functional intestinal cell types including enterocytes, goblet, Paneth and enteroendocrine cells. In some aspects, human PSCs are efficiently directed to differentiate in vitro into intestinal epithelium that may include secretory, endocrine and absorptive cell types. It will be understood that molecules such as growth factors may be added to any stage of the development to promote a particular type of intestinal tissue formation.

[0063] PSCs, such as ESCs and iPSCs, undergo directed differentiation in a step-wise or non-step-wise manner first into definitive endoderm (DE) then into mid/hindgut epithelium and mesenchyme (*e.g.*, hindgut spheroids), and then into intestinal tissue. In some aspects, definitive endoderm cells and hESCs are treated with one or more growth factors.

[0064] In some aspects, soluble FGF and Wnt ligands are used to mimic early hindgut specification in culture to convert, through directed differentiation, DE

developed from iPSCs or ESCs into hindgut epithelium that efficiently gives rise to all the major intestinal cell types. In human, directed differentiation of DE is achieved through selective activating certain signaling pathways that are important to intestinal development. It will be understood by one of skill in the art that altering the expression of any Wnt signaling protein in combination with any FGF ligand can give rise to directed differentiation as described herein.

[0065] More details are found, for example, in Liu *et al.*, "A small-molecule agonist of the Wnt signaling pathway," *Angew Chem Int Ed Engl.* 44(13):1987-1990 (2005); Miyabayashi *et al.*, "Wnt/beta-catenin/CBP signaling maintains long-term murine embryonic stem cell pluripotency," *Proc Natl Acad Sci U S A.* 104(13):5668-5673 (2007); Zhang *et al.*, "Small-molecule synergist of the Wnt/beta-catenin signaling pathway," *Proc Natl Acad Sci U S A.* 104(18):7444-7448 (2007); Neiiendam *et al.*, "An NCAM-derived FGF-receptor agonist, the FGL-peptide, induces neurite outgrowth and neuronal survival in primary rat neurons," *J Neurochem.* 91(4):920-935 (2004); Shan *et al.*, "Identification of a specific inhibitor of the dishevelled PDZ domain," *Biochemistry* 44(47):15495-15503 (2005); Coghlan *et al.*, "Selective small molecule inhibitors of glycogen synthase kinase-3 modulate glycogen metabolism and gene transcription," *Chem Biol.* 7(10):793-803 (2000); Coghlan *et al.*, "Selective small molecule inhibitors of glycogen synthase kinase-3 modulate glycogen metabolism and gene transcription," Chemistry & Biology 7(10):793-803; and Pai *et al.*, "Deoxycholic acid activates beta-catenin signaling pathway and increases colon cell cancer growth and invasiveness," *Mol Biol Cell.* 15(5):2156-2163 (2004); each of which is hereby incorporated by reference in its entirety.

[0066] In some aspects, siRNA and/or shRNA targeting cellular constituents associated with the Wnt and/or FGF signaling pathways are used to activate these pathways.

[0067] Modulators/activators of the Wnt signaling pathway include Wnt1, Wnt2, Wnt2b, Wnt3, Wnt3a, Wnt4, Wnt5a, Wnt5b, Wnt6, Wnt7a, Wnt7b, Wnt8a, Wnt8b, Wnt9a, Wnt9b, Wnt10a, Wnt10b, Wnt11, and Wnt16. In some aspects, the

modulation of the pathway may be through the use of small molecule modulators or protein modulators that activate the aforementioned pathways or proteins that activate the aforementioned pathways. For example, Small molecule modulators of the Wnt pathway included, but is not limited to Lithium Chloride; 2-amino-4,6-disubstituted pyrimidine (hetero) arylpyrimidines; IQ1; QS11; NSC668036; DCA beta-catenin; 2-amino-4-[3,4-(methylenedioxy)-benzyl-amino]-6-(3-methoxyphenyl) pyrimidine. Exemplary natural inhibitors of Wnt signaling include but are not limited to Dkk1, SFRP proteins and FrzB. In some aspects, the extrinsic molecules include but are not limited to small molecules such as WAY-316606; SB-216763; or BIO (6-bromoindirubin-3'-oxime). In some aspects, siRNA and/or shRNA targeting cellular constituents associated with the Wnt and/or FGF signaling pathways may be used to activate these pathways. It would be understood by one of skill in the art that the target cellular constituents include but are not limited to SFRP proteins; GSK3, Dkk1, and FrzB. Additional modulators include molecules or proteins that inhibit GSK3, which activates the Wnt signaling pathway. Exemplary GSK3 inhibitors include, but are not limited to: Chiron/ CHIR99021, for example, which inhibits GSK3β. One of ordinary skill in the art will recognize GSK3 inhibitors suitable for carrying out the disclosed methods. The GSK3 inhibitor may be administered in an amount of from about 1 uM to about 100 uM, or from about 2 uM to about 50 uM, or from about 3 uM to about 25 uM. One of ordinary skill in the art will readily appreciate the appropriate amount and duration.

[0001] Fibroblast growth factors (FGFs) are a family of growth factors involved in angiogenesis, wound healing, and embryonic development. In some aspects, it will be understood by one of skill in the art that any of the FGFs can be used in conjunction with a protein from the Wnt signaling pathway. In some aspects, soluble FGFs include and but are not limited to FGF4, FGF2, and FGF3. In some embodiments, the FGF signaling pathway is activated by contacting the precursor cell with one or more molecules selected from the group consisting of FGF1, FGF2, FGF3, FGF4, FGF10, FGF11, FGF12, FGF13, FGF14, FGF15, FGF16, FGF17, FGF18, FGF19,

FGF20, FGF21, FGF22, and FGF23. In some embodiments, siRNA and/or shRNA targeting cellular constituents associated with the FGF signaling pathway may be used to activate these pathways. It will be understood by one of skill in the art that the methods and compositions described herein in connection with the Wnt and FGF signaling pathways are provided by way of examples. Similar methods and compositions are applicable to other signaling pathways disclosed herein.

[0068] In some aspects, DE culture is treated with the one or more modulators of a signaling pathway described herein for 6 or more hours; 12 or more hours; 18 or more hours; 24 or more hours; 36 or more hours; 48 or more hours; 60 or more hours; 72 or more hours; 84 or more hours; 96 or more hours; 120 or more hours; 150 or more hours; 180 or more hours; 200 or more hours, 240 or more hours; 270 or more hours; 300 or more hours; 350 or more hours; 400 or more hours; 500 or more hours; 600 or more hours; 700 or more hours; 800 or more hours; 900 or more hours; 1,000 or more hours; 1,200 or more hours; or 1,500 or more hours.

[0069] In some aspects, DE culture is treated with the one or more modulators of a signaling pathway described herein at a concentration of 10 ng/ml or higher; 20 ng/ml or higher; 50 ng/ml or higher; 75 ng/ml or higher; 100 ng/ml or higher; 120 ng/ml or higher; 150 ng/ml or higher; 200 ng/ml or higher; 500 ng/ml or higher; 1,000 ng/ml or higher; 1,200 ng/ml or higher; 1,500 ng/ml or higher; 2,000 ng/ml or higher; 5,000 ng/ml or higher; 7,000 ng/ml or higher; 10,000 ng/ml or higher; or 15,000 ng/ml or higher. In some aspects, concentration of signaling molecule is maintained at a constant throughout the treatment. In other aspects, concentration of the modulators of a signaling pathway is varied during the course of the treatment. In some aspects, a signaling molecule in accordance with the present invention is suspended in media comprising DMEM and fetal bovine serine (FBS). The FBS can be at a concentration of 2% and more; 5% and more; 10% or more; 15% or more; 20% or more; 30% or more; or 50% or more. One of skill in the art would understand that the regiment described herein is applicable to any known modulators of the signaling pathways

described herein, alone or in combination, including but not limited to any molecules in the Wnt and FGF signaling pathways.

[0070] In aspects where two or more signaling molecules are used to treat the DE culture, the signaling molecules can be added simultaneously or separately. When two or more molecules are use, the concentration of each may be varied independently.

[0071] Expression of CDX2 may be used to reveal tendency of hindgut formation after DE have been incubated with an FGF signaling activator and a Wnt signaling activator, for example, FGF4 and Wnt3a, for a period of time, for example, for 12 hours or longer; 18 hours or longer; 24 hours or longer; 36 hours or longer; 48 hours or longer; 60 hours or longer; or 90 hours or longer. In some aspects, longer periods of incubation are needed to achieve a stable posterior endoderm phenotype as measured by prolonged expressed of CDX2. In such aspects, the periods of incubation can be for 60 hours or longer; 72 hours or longer; 84 hours or longer; 96 hours or longer; 108 hours or longer; 120 hours or longer; 140 hours or longer; 160 hours or longer; 180 hours or longer; 200 hours or longer; 240 hours or longer; or 300 hours or longer.

[0072] Alternatively, in some aspects, the absence of cellular constituents, such as foregut markers Sox2, Pdx1, Cldn18, and Albumin, can be used to reveal directed hindgut formation. In some aspects, intestinal transcription factors CDX2, KLF5 and SOX9 can be used to represent intestinal development. In some aspects, GATA6 protein expression can be used to represent intestinal development. In these aspects, the periods of incubation can be for 12 hours or longer; 18 hours or longer; 24 hours or longer; 36 hours or longer; 48 hours or longer; 60 hours or longer; or 90 hours or longer. Alternatively, the periods of incubation can be for 60 hours or longer; 72 hours or longer; 84 hours or longer; 96 hours or longer; 108 hours or longer; 120 hours or longer; 140 hours or longer; 160 hours or longer; 180 hours or longer; 200 hours or longer; 240 hours or longer; or 300 hours or longer.

[0073] In some aspects, abundance data of cellular constituents, for example, protein and/or gene expression levels, are determined by immunohistochemistry using primary and/or secondary antibodies targeting molecules in the relevant signaling pathways. In other aspects, abundance data of cellular constituents, for example, protein and/or gene expression levels, are determined by microarray analyses.

[0074] Still alternatively, morphological changes can be used to represent the progress of directed differentiation. In some aspects, hindgut spheroids are further subject to 3-dimensional culture conditions for further maturation. In other aspects, a highly convoluted epithelium surrounded by mesenchymal cells can be observed following hindgut spheroids formation. Additionally, intestinal organoids; polarized columnar epithelium; goblet cells; or smooth muscle cells can be observed in 6 days or longer; 7 days or longer; 9 days or longer; 10 days or longer; 12 days or longer; 15 days or longer; 20 days or longer; 25 days or longer; 28 days or longer; 32 days or longer; 36 days or longer; 40 days or longer; 45 days or longer; 50 days or longer; or 60 days or longer.

[0075] MID/HINDGUT SPHEROIDS TO COLON ORGANOIDS

[0076] It has been identified that, in addition to FGF and WNT signaling, Bone Morphogenetic Proteins (BMP) specifically BMP2 and BMP4, are capable of promoting a posterior/hindgut fate and repressing foregut fate. Additionally, BMP signaling regulates formation of distinct regional types of intestine. Inhibition of BMP with noggin after the hindgut stage promotes a proximal intestinal fate (duodenum/jejunum). Activation of BMP signaling after the hindgut stage promotes a more distal intestinal cell fate (cecum/colon).

[0077] Activation of BMP can be carried out by contacting the mid/hindgut spheroids with a BMP activator and an EGF signaling pathway activator for a period of time sufficient to form said human colon organoid. The demarcation of the incubation period may be defined by the point in time in which the human colon organoid

expresses SATB2. Suitable BMP activators and EGF signaling pathway activators will be readily appreciated by one of ordinary skill in the art. Suitable BMP activators may include, for example BMP2, BMP4, BMP7, BMP9 and protein or small molecule agonists such as ventromorphins (Genthe et al. 2017) or proteins that serve as agonists. The BMP activator and EGF signaling pathway activator may be contacted with the mid-/hindgut spheroids for from about 1 day to about 3 days. BMP signaling may be activated within the first three days. In one aspect, the contacting step of the BMP activator and EGF signaling pathway activator is from 24 hours to about 10 days, or from about 48 hours to about 9 days, or from about 3 days to about 8 days, or from about 4 days to about 8 days, or from about 5 days to about 7 days. Suitable EGF activators may include, for example TGF alpha, HB-EGF, Amphiregulin, Epigen, Betacellulin and small molecules such as db-cAMP. The EGF activator may be contacted with the mid-/hindgut spheroids at a concentration of from about 10ng/mL to 10,000 ng/ML, for a time period of from about 24 hours to about 10 days, or from about 48 hours to about 9 days, or from about 3 days to about 8 days, or from about 4 days to about 8 days, or from about 5 days to about 7 days.

[0078] The mid/hindgut spheroids may be contacted with a BMP activator and/or EGF activator at a concentration of 5 ng/ml or higher; 20 ng/ml or higher; 50 ng/ml or higher; 75 ng/ml or higher; 100 ng/ml or higher; 120 ng/ml or higher; 150 ng/ml or higher; 200 ng/ml or higher; 500 ng/ml or higher; 1,000 ng/ml or higher; 1,200 ng/ml or higher; 1,500 ng/ml or higher; 2,000 ng/ml or higher; 5,000 ng/ml or higher; 7,000 ng/ml or higher; 10,000 ng/ml or higher; or 15,000 ng/ml or higher, alone or combined. In some embodiments, concentration of signaling molecule is maintained at a constant throughout the treatment. In other embodiments, concentration of the molecules of a signaling pathway is varied during the course of the treatment. In some embodiments, a signaling molecule in accordance with the present invention is suspended in media comprising DMEM and fetal bovine serine (FBS). The FBS can be at a concentration of 2% and more; 5% and more; 10% or more; 15% or more; 20% or more; 30% or more; or 50% or more. One of skill in the art would understand that the

regiment described herein is applicable to any known molecules of the signaling pathways described herein, alone or in combination

[0079] Examples

[0080] The following non-limiting examples are provided to further illustrate aspects of the invention disclosed herein. It should be appreciated by those of skill in the art that the techniques disclosed in the examples that follow represent approaches that have been found to function well in the practice of the invention, and thus can be considered to constitute examples of modes for its practice. However, those of skill in the art should, in light of the present disclosure, appreciate that many changes can be made in the specific aspects that are disclosed and still obtain a like or similar result without departing from the spirit and scope of the invention.

[0081] The epithelium of the gastrointestinal tract is derived from the definitive endoderm, one of the primary germ layers that are established during gastrulation. The process of gut tube morphogenesis transforms the definitive endoderm into a primitive gut tube with a foregut, midgut and hindgut. The midgut gives rise to the small and proximal large intestine and the hindgut gives rise to the distal large intestine and rectum (Zorn and Wells, 2009). The small intestine is further subdivided into 3 segments: The duodenum which is involved in absorption of nutrients and uptake of iron, the jejunum which is involved in the digestion and absorption of nutrients and the ileum which is involved in the absorption of bile acids and vitamin-B12 (Jeejeebhoy, 2002). The large intestine is subdivided in to the cecum, colon and rectum which are all involved in absorption of water and electrolytes (Jeejeebhoy, 2002). Although recent advances have shed light into the development of the small intestine (Finkbeiner et al., 2015; Spence et al., 2011; Watson et al., 2014), little is known about development of human large intestine/colon. Furthermore, diseases affecting this region of the gastrointestinal (GI) tract, colitis, colon cancer, polyposis syndromes and Irritable Bowel Syndrome are prevalent (Molodecky et al., 2012; Siegel et al., 2014; Zbuk and Eng, 2007). Animal models of polyposis syndromes and intestinal cancer are

limited since polyps and tumors preferentially form in the small intestine and rarely in the colon or rectum (Haramis et al., 2004; He et al., 2004; Moser et al., 1990).

[0082] Applicant previously described a method in which human pluripotent stem cells can be differentiated into intestinal tissue through steps of directed differentiation that approximate embryonic development of the small intestine. First, pluripotent stem cells are differentiated into definitive endoderm by treatment with Activin A. Exposure of definitive endoderm to high levels of Wnt and FGF induces morphogenesis into mid/hindgut tube spheroids. Once formed, these midgut/hindgut spheroids, when grown in 3-dimensional culture under conditions that favor intestinal growth, transition through stages that approximate small intestinal development in vivo and form human intestinal organoids (HIOs) (Spence et al., 2011). HIOs have a small intestinal identity and have proven extremely useful for modeling small intestinal biology (Bouchi et al., 2014; Finkbeiner et al., 2015; Watson et al., 2014; Xue et al., 2013). However, until now, PSC-derived large intestinal organoids have not been developed, and given the prevalence of disease in the large intestine, such a system would allow for interrogation of development and disease mechanisms in this region of the GI tract.

[0083] To develop a method for generating large intestinal organoids, Applicant first identified Satb2 as a definitive marker of the presumptive large intestinal epithelium in frogs, mice, and humans. Using Satb2 as a marker, Applicant has shown that BMP signaling is required for specification of posterior gut endoderm of frogs and mice, consistent with the known role of BMP in posterior-ventral development (Kumar et al., 2003; Roberts et al., 1995; Sherwood et al., 2011; Tiso et al., 2002; Wills et al., 2008). Moreover, stimulation of BMP signaling in PSC-derived gut tube cultures for 3 days is sufficient to induce a posterior HOX code and the formation of SATB2-expressing colonic organoids. Human colonic organoids (HCOs) had a marker profile and cell types consistent with large intestine. Furthermore, HCOs, but not HIOs, formed colonic enteroendocrine cells (EEC) in response to expression of NEUROG3, demonstrating that HCOs were functionally committed to the colonic region. In

addition, HCOs engrafted under the kidney capsule of immunocompromised mice and grown in vivo for 8-10 weeks, maintain their regional identify, formed tissues with colonic morphology, contained colon-specific cell types, had zones of proliferation and differentiation, as well as well-formed smooth muscle layers. Intestinal enteroids and colonoids that were derived from *in vivo* grown organoids maintained regional identify. Lastly, RNA-seq analysis demonstrated that HIOs and HCOs underwent substantial maturation and express regional markers consistent with a small and large intestinal identity respectively. In summary, Applicant identified an evolutionarily conserved BMP-HOX pathway in frogs and mice and used this to direct hindgut patterning and formation of human colonic organoids.

[0084] RESULTS

[0085] SATB2 expression marks the gut endoderm of posterior embryonic and adult intestine.

[0086] The molecular pathways that establish the mid and hindgut, the presumptive small and large intestine, are poorly understood, in part due to a paucity of well-defined markers. This has limited the ability to direct the differentiation of human PSCs into regionally distinct intestinal organoids, in particular large intestinal organoids. Applicant therefore identified markers that distinguish different domains of the mouse embryonic gut tube and used these to interrogate signaling pathways that pattern the early intestine. Consistent with previous reports Applicant found that in e9.5 mouse embryos, Gata4 marked the gut endoderm from the posterior foregut to the yolk stalk (FIG. 8A) (Aronson et al., 2014; Battle et al., 2008; Beuling et al., 2008a; Beuling et al., 2007a; Beuling et al., 2007b; Beuling et al., 2010; Beuling et al., 2008b; Bosse et al., 2007; Kohlnhofer et al., 2016; Patankar et al., 2012a; Patankar et al., 2012b; Sherwood et al., 2009; Walker et al., 2014). At later stages of development (e11.5-e16.5), Gata4 continued to distinctly mark the anterior but not the posterior intestine (FIG. 8B-D,I-J). This expression domain remains intact into adulthood in both mice (not shown) and humans (FIG. 8K-L).

[0087] In order to identify markers of the posterior fetal intestine, Applicant mined public expression databases such as GNCProTM, TiGER and Human Protein Atlas for colon enriched genes (described in the Materials and Methods section) and found Satb2 as a potential marker of large intestine. Satb2 is a member of the CUT-class of homeobox genes (Holland et al., 2007), which binds nuclear matrix attachment regions and is involved in chromatin remodeling (Gyorgy et al., 2008). Immunostaining showed that Satb2 protein was first detected in the posterior endoderm of mouse embryos at e9-9.5 and formed a discreet expression boundary with Gata4 (FIG. 8A) at the yolk stalk, suggesting that the Satb2+ domain marks the posterior intestine, a broader expression domain than previously identified (Dobreva et al., 2006). Satb2 expression continued to mark the posterior intestinal endoderm throughout development (e11.5-16.5) (FIG. 8 B, C, E, F, H, J) and in the postnatal colon in mice (not shown) and humans (FIG. 8L). Using published human proteome and RNA-seq data, Applicant confirmed that GATA4 and SATB2 differentially mark proximal and distal regions of the human fetal and adult intestinal tract respectively (Bernstein et al., 2010; Fagerberg et al., 2014) (Wang et al., 2015) (FIG. 9A-C). These data demonstrate that the Gata4 and Satb2 expression boundaries are established early during development of mouse and marks future boundaries of the developing small and large intestine in mice and humans.

[0088] BMP signaling is required for Satb2 expression in the embryonic hindgut endoderm.

[0089] Applicant next used Satb2 as a marker to identify pathways that promote posterior intestinal fate in embryos. Applicant first determined if BMP signaling was active in the posterior gut tube, given its known role in patterning endoderm at several stages of development in zebrafish, Xenopus, chick and mouse (Kumar et al., 2003; Roberts et al., 1995; Sherwood et al., 2011; Tiso et al., 2002; Wills et al., 2008). Applicant observed that BMP signaling was highly active in the endoderm and mesoderm of the posterior gut tube of e8.5 mouse embryos as measured by phosphorylated Smad1/5/8 (pSMAD1/5/8) (FIG. 1A-B). To determine if BMP

signaling is required for patterning of the posterior gut tube, Applicant cultured early headfold stage mouse embryos (e7.5) in the BMP signaling inhibitor DMH-1 (FIG. 1C). After 48 hours of DMH-1 treatment, Applicant saw a significant reduction in pSmadl/5/8 levels and a loss of Satb2 expression in the posterior gut tube (FIG. 2D-K). In addition, Satb2 expression was lost in the first brachial arch of DMH-1 treated embryos consistent with previous studies in Zebrafish (Sheehan-Rooney et al., 2013). DMH-1 had no impact on TGFI3 signaling as measured by pSmad2/3 levels (FIG. 1F). Given the evolutionary conservation of the Satb2 across vertebrate species (Li et al., 2006) Applicant investigated if BMP is required for Satb2 expression in the hindgut of frog embryos (FIG. 2L). Similar to mice, treatment of Xenopus embryos with DMH-1 (FIG. 1M-V), or transgenic expression of the BMP-antagonist Noggin (not shown) resulted in a loss of Satb2 expression in the hindgut and brachial arches. BMP signaling has been shown to directly regulate Satb2 expression in mouse embryonic mandibles through direct binding of Smad1/5 to a conserved enhancer (Bonilla-Claudio et al., 2012), suggesting that Satb2 may be a direct BMP target in the gut as well. Taken together these results revealed a conserved pathway in vertebrates whereby BMP signaling is required for defining the posterior most region of the developing gut tube that gives rise to the distal ileum and large intestine.

[0090] BMP signaling promotes posterior fate in human gut tube cultures.

[0091] Applicant next investigated if BMP signaling could be used to promote a posterior gut tube fate in humans using nascent CDX2+ gut tube spheroids derived from human PSCs as previously described (Spence et al., 2011). Applicant either inhibited or activated BMP signaling using the BMP inhibitor NOGGIN or BMP2 respectively (FIG. 2A) and monitored BMP signaling levels by accumulation of nuclear pSMAD1/5/8. Control cultures had low levels of pSMAD1/5/8 protein and addition of NOGGIN abolished this staining (FIG. 2B-D). In contrast, addition of BMP2 caused a rapid accumulation of pSMAD158 in both epithelial and mesodermal cells suggesting both cell types respond to BMP signals similar to what Applicant

observed in mouse embryos (FIG. 1A-B). The specificity of pSmadl/5/8 staining was confirmed using adult mouse colon, which showed pSmad1/5/8 staining restricted to the differentiated compartment of the upper crypt (FIG. 2E) as previously reported (Hardwick et al., 2004; van Dop et al., 2009; Whissell et al., 2014). Further analysis of organoids revealed that 3 days of BMP2 treatment was sufficient to induce high levels of SATB2 protein in the epithelium compared to NOGGIN and control cultures (FIG. 2F-I). This suggests that a short pulse of BMP activity is sufficient to pattern spheroid endoderm into a posterior gut tube fate.

[0092] While BMP signaling is known to regulate anterior-posterior patterning of the endoderm, little is known about the transcriptional networks that ultimately confer positional identity along the A-P axis in mammals. Applicant used human gut tube spheroids and RNA-seq to identify how BMP signaling establishes posterior domains in the developing human gut. Principal component analysis revealed that gut tube spheroids treated with BMP for 3 days clustered separately from NOGGIN and control treated organoids (FIG. 2J). Examination of gene ontology terms (GO terms) revealed that modulation of BMP signaling affects multiple biological processes including organ morphogenesis, cell-cell signaling, pattern specification and cellular response to BMP signaling (FIG. 2K). The most definitive regulators of A-P patterning are HOX genes, and Applicant found that BMP activation resulted in down regulation of anterior HOX genes and up regulation of posterior HOX genes (FIG. 2L). In particular Applicant saw BMP-mediated increases in multiple paralogs of HOX10, 11, 12 and 13 groups. These results demonstrate that BMP signaling broadly regulates A-P hox code during patterning of the human gut tube and suggest a mechanism by which the distal GI tract is initially specified.

[0093] BMP signaling acts downstream of SHH to induce a posterior HOX code.

[0094] Previous studies suggest that Sonic Hedgehog (Shh) acts upstream of Bmp4 and Hox13 expression during posterior gut patterning in chick embryos (FIG. 10A) (Roberts et al., 1995). However, the relative epistatic relationship between BMP

and Hox13 (FIG. 10B) was not investigated due to embryonic lethality caused by Bmp4 overexpression in the midgut and hindgut (De Santa Barbara et al., 2005; Roberts et al., 1995). Applicant used human gut tube cultures to better model the epistatic relationship of SHH-BMP-HOX13 during posterior gut tube patterning. Activation of hedgehog signaling with the smoothened agonist SAG led to a concentration dependent activation of the BMP signaling target gene MSX2 and the mesenchymal HOX factors, HOXA13 and HOXD13 (FIG. 10C). However, SAG-mediated activation of these factors was only a fraction of the activation mediated by BMP2 (FIG. 10C). Applicant further showed that the ability of HH signaling to activate HOXA13 was entirely dependent on BMP (FIG. 10D-E), confirming that BMP signaling functions downstream of SHH as previously reported (Shyer et al., 2015; Walton et al., 2012; Walton et al., 2009; Walton et al., 2016). It has not been determined if BMP signaling is sufficient to activate the posterior HOX program downstream of HH signaling. Applicant therefore examined HOXA13 induction by BMP in the presence of the SHH inhibitor Cyclopamine and found that BMP2 was sufficient to induce HOXA13 when SHH signaling is inhibited (FIG. 10F-G). Consistent with this, activation of SHH signaling during BMP patterning did not improve SATB2 expression (FIG. 11A). Experiments in Xenopus confirmed this epistatic relationship between SHH and BMP (data not shown) suggesting that this mechanism is evolutionarily conserved. Taken togetherApplicant's data suggest that BMP signaling is sufficient to activate the posterior HOX code and does so downstream of HH signaling.

[0095] BMP-derived organoids cultured in vitro maintain a distal identity.

[0096] Applicant next investigated if 3 days of BMP treatment is sufficient to confer stable regional identity following extended culture of organoids for 25 days (FIG. 3). Levels of ONECUT1 (a marker of proximal small intestine) were highest in NOGGIN and control treated organoids and absent in BMP2 treated organoids (FIG. 3A-D). Conversely, SATB2 was absent in the epithelium of NOGGIN and control treated organoids but broadly expressed in nearly all of the CDX2+ epithelial cells of

BMP2 treated organoids (FIG. 3 E-H, FIG. 11A). Importantly, modulation of BMP signaling had similar proximal-distal patterning effects on multiple human PSC lines, including embryonic stem cell lines H1 and H9 and induced pluripotent stem cell lines (IPSC 54.1 and IPSC 72.3) (shown below). Applicant frequently observed non-epithelial SATB2 expression in NOGGIN and control organoids (data not shown) possibly due to the presence of other cell types that are known to be present in HIOs in vitro (Spence et al., 2011). Examination of HOXB13 and HOXD13, which is expressed in posterior epithelium and mesenchyme respectively, further revealed that BMP treated organoids maintained posterior patterning following prolonged culture in vitro (FIG. 11B-C).

[0097] Goblet cells are distributed in a low-to-high gradient from proximal small intestine to distal large intestine (Rodriguez-Pineiro et al., 2013), and Applicant investigated if goblet cell numbers were lower in proximal and higher in distal organoids. Analysis of MUC2 staining at 28 days revealed that BMP2 treated organoids had high numbers of goblet cells as visualized by intracellular MUC2 (FIG. 3I-L) as compared to more proximal NOGGIN treated and control organoids, which only had rare intracellular MUC2 staining. Applicant further confirmed the regional identity of goblet cells using the marker MUC5B, which is expressed by a subset of goblet cells in the colon but not in the small intestine (van Klinken et al., 1998). MUC5B staining was absent in Noggin and control treated 28-day organoids but was present in BMP2 treated organoids (FIG. 4M-P). Goblet cell morphology became more mature in older organoids (FIG. 11D-I), where in 44-day old BMP treated organoids Applicant observed goblet cells in the process of secreting mucus into the lumen of the organoids (FIG. 11J-L). The ability to observe mucus secretion in BMP treated organoids suggests that this organoid system would be useful to study mucus secretion and the roles of mucus in intestinal pathophysiology.

[0098] While the regional pattern of organoids is stable after 28 days in culture, Applicant wanted to investigate if early patterning was fully established after the initial 3-day treatment. To do so, Applicant shifted 3-day NOGGIN-treated

spheroids to BMP2-containing media for 3 days and conversely shifted 3-day BMP treated spheroids to NOGGIN-containing media for 3 days. Proximal organoids generated with NOGGIN did not express SATB2 in response to BMP2 demonstrating that proximal fate was stable following 3 days of patterning (FIG. 11A). In the converse experiment, while 3 days of BMP2 treatment was sufficient to induce a stable distal fate, a subset of organoids lost SATB2 expression in response to NOGGIN treatment (FIG. 11A). While 3 days of BMP2 treatment is sufficient to induce a colonic fate that is stable in vitro and in vivo (FIG. 12), there remains plasticity in the early posterior gut tube. This is consistent with the observation that the colonic endoderm of midgestation rat embryos is more regionally plastic than the small intestinal endoderm (Ratineau et al., 2003).

[0099] Patterning of organoid mesenchyme by BMP signaling.

[00100] While stimulation of BMP signaling conferred regional identity to organoid epithelium, Applicant also observed pSMAD1/5/8 in the non-epithelial compartment of BMP2 treated organoids during patterning, and upregulation of posterior HOX factors known to be expressed in the mesenchyme. To determine if mesenchymal patterning was stable, or required continued patterning input from epithelium, Applicant isolated and expanded mesenchymal cell cultures for 2-3 weeks and analyzed them for expression of regional HOX genes. Mesenchymal cultures were lacking E-cadherin expressing cells, suggesting that they were primarily comprised of mesenchyme (FIG. 3Q). Analysis of HOXD3, which is enriched in proximal intestinal mesenchyme (Yahagi et al., 2004), confirmed that the mesenchyme from NOGGIN and control treated organoids have a stable proximal identity while BMP treated organoids had decreased expression of HOXD3 (FIG. 3R) and high levels HOXA13 (FIG. 3S), which continues to be expressed in human colon fibroblasts (Higuchi et al., 2015). Taken together, these data suggest that early modulation of BMP signaling patterns both the epithelium and the mesenchyme and that mesenchymal patterning is stable even in the absence of epithelium.

[00101] Induction of colonic enteroendocrine cells is restricted to BMP2 treated organoids.

[00102] The development of several ECC subtypes is regionally restricted to specific segments of small and large intestine. For example, expression of the protein INSL5 is restricted to colonic EECs (Burnicka-Turek et al., 2012; Thanasupawat et al., 2013). As a functional test of colonic identity, Applicant determined if experimental induction of the colonic EEC marker INSL5 was restricted to BMP2-treated distal organoids. To do this Applicant inducibly expressed the proendocrine transcription factor NEUROG3 using an iPSC line harboring a doxycycline (DOX) inducible NEUROG3 expression cassette (FIG. 4A) as previously described (McCracken et al., 2017; McCracken et al., 2014). Applicant performed a 6-hour pulse of DOX and after an additional 7 days in culture observed a robust induction of EECs as measured by CHGA positive cells (FIG. 4B-I). However, Applicant only observed INSL5 positive cells in BMP2 treated organoids and confirmed this by QPCR analysis (FIG. 4C-H,J). Given that INSL5-expressing cells are only in the colon, Applicant's data strongly suggest that BMP2-treated organoids are functionally committed to the colonic fate. The expression of distal markers like SATB2, MUC5B and HOXA13 and the competence to generate colon specific ECCs support the conclusion that BMP2 treated organoids are colonic, and thus will be referred to as human colonic organoids (HCOs).

[00103] Regional identity of patterned organoids is maintained in vivo.

[00104] Previous studies of mouse and human fetal intestine have demonstrated that regional identity and tissue morphology of different regions of the intestine were maintained following orthotopic transplantation and growth in immunocompromised mice (Duluc et al., 1994; Savidge et al., 1995). To determine if HIOs and HCOs that were patterned in vitro would maintain regional identity and grow into small and large intestinal tissue, Applicant transplanted them under the mouse kidney capsule for 6-10 weeks, which Applicant previously demonstrated results in HIO maturation into small intestinal tissue (Watson et al., 2014). Applicant observed that the engraftment of NOGGIN and control HIOs was more efficient than HCOs (FIG.

12A). Consistent with their regional identity, transplanted HIOs and HCOs developed into mature tissues that morphologically resembled either small or large intestine, respectively (FIG. 5A-E). The epithelium of NOGGIN and control organoids formed well-defined crypts and tall villi, comparable to human small intestine. In contrast BMP2-treated organoids contained crypts but lacked villi, similar to colon.

[00105] In addition to their morphological resemblance to either small or large intestine, transplanted HIOs and HCOs expressed distinct regional markers and contained regionally enriched cell types. For example, the majority of the epithelium of NOGGIN and control HIOs expressed the proximal marker GATA4 and did not express the large intestinal marker SATB2 (FIG. 5F-I, K-N, FIG. 12B-E). Conversely HCO epithelia were uniformly SATB2+ but did not express GATA4 (FIG. 5J,0, FIG. 12B-E). In addition, Paneth cells expressing DEFA5 were present in the crypts of NOGGIN and control HIOs, but were absent HCOs (FIG. 5P-T, FIG. 12F) similar to the human colon (Wehkamp et al., 2006). Applicant further confirmed the colonic identity of HCOs using the colonic goblet cell marker MUC5B (van Klinken et al., 1998), which is expressed by a subset of goblet cells of HCOs but is not detectible in NOGGIN or control HIOs (FIG. 5U-Y, FIG. 12G). Additionally, the number of MUC2+ goblet cells was vastly higher in HCOs compared HIOs consistent with the abundance of goblet cells seen in the human colon (FIG. 12H-L). The patterning markers, the presence of MUC5B-expressing goblet cells, and the absence of Paneth cells all support the conclusion that transplanted HCOs have colonic epithelium.

[00106] In vivo matured HIOs and HCOs express regional enteroendocrine hormones.

[00107] There are at least 12 major EEC subtypes that are found in different regions of the gastrointestinal tract and Applicant analyzed HIOs and HCOs for the presence of regional EECs. Ghrelin and Motilin are found predominantly in the proximal intestine, and correspondingly these hormones were largely expressed in NOGGIN and control HIOs but not HCOs (FIG. 6A-D). Similarly, GIP, which is found in K-cells of the small intestine but is absent in the colon, were found in NOGGIN and

control HIOs but not in HCOs (FIG. 6E-H). Applicant then examined presence of distally enriched EECs in HCOs by analyzing for expression of GLP-1 and PYY, which are more abundant in the colon. Applicant observed higher numbers of GLP-1 and PYY cells and higher expression of preproglucagon and PYY in HCOs than in HIOs (FIG. 61-P). In addition, Applicant found expression of the colon specific hormone INSL5 (Burnicka-Turek et al., 2012; Thanasupawat et al., 2013), only in HCOs (FIG. 6Q-T).

[00108] Analysis of stem and progenitor cells in HIOs and HCOs in vitro and in vivo.

[00109] To determine if in vitro-derived HIOs and HCOs express markers of stem and progenitor cells, Applicant used the H9-BAC-LGR5-eGFP transgenic line that has been described previously (McCracken et al., 2014; Watson et al., 2014). Examination of LGR5-eGFP expression in organoids revealed expression in broad epithelial domains similar to the expression patterns in Lgr5-eGFP mice as early as e13.5 (Shyer et al., 2015) (FIG. 13 A, B, F, G, K, L). GFP expression was also evident outside the epithelium of organoids as determined by histology and FACS analysis which revealed a population of GFP+ EPCAM- cells (data not shown). In addition, Applicant examined the expression of SOX9, which is a marker of progenitor cells in the fetal and adult intestine and found it expressed in the epithelium of both HIOs and HCOs (FIG. 13C-E, H-J, M-0). These data suggest that embryonic/fetal intestinal progenitor cells, marked by LGR5-eGFP and SOX9, are present in HIOs and HCOs in vitro.

[00110] At later stages of intestinal development, progenitor cells become restricted to the base of developing villi, where they will eventually contribute to the intestinal stem cells (ISCs) of the crypts of Lieberkuhn. To determine if the progenitor cells that Applicant observed in vitro will undergo this this developmental transition, Applicant transplanted HIOs and HCOs and monitored LGR5-eGFP, SOX9, and KI67 protein. Following maturation of organoids in vivo, Applicant observed LGR5-eGFP, SOX9, and KI67 restricted to the base presumptive crypts (FIG. 13P-X). In addition, SOX9 was also observed in EECs in the villi of HIOs and in the cuff of the colonic

epithelium transplanted HCOs consistent with SOX9 expression in these cell types. Given that Sox9 and Lgr5 mark intestinal and colonic stem cells capable of forming enteroids and colonoids in mice (Gracz et al., 2010; Ramalingam et al., 2012) Applicant investigated if the epithelium of transplanted organoids could be isolated and used to generate enteroids and colonoids. Both HIOs and HCOs gave rise to cultures of epithelial organoids that grew and could be passaged (FIG. 13Y-A'). Moreover, HCO-derived epithelial cultures expressed the colonic markers CKB, FXYD3, SATB2, and HOXB13 but did not express the proximal small intestine markers PDX1 or GATA4 suggesting that regional identity was maintained (FIG. 13B'-D'). These data suggest that HIOs and HCOs grown in vivo contain progenitor and stem cells.

[00111] Global transcriptional analysis of HIOs and HCOs.

[00112] In order to broadly interrogate the regional identity and maturation of HIOs and HCOs, Applicant performed RNA-seq analysis of HIOs and HCOs grown in vivo and compared them with published data sets of human fetal and adult small and large intestines. Principal component analysis revealed that primary tissues isolated from adult and fetal intestine clustered together along principle component 1 (PC1) axis, which accounted for 36.5% of the cumulative variation among samples (FIG. 14A). A GO analysis revealed that this variation was due to cell types that were present only in primary tissues and not PSC-derived transplants. For example, 6 of the top 10 biological processes present in human primary tissues and absent in transplants were related to immune cells (FIG. 14B-C). The second principle component (PC2) accounts for 17.7% of cumulative variation and separates the samples according to maturity (FIG. 7A). This component revealed that transplanted organoids are more mature than human fetal intestine and fetal colon but not as mature as adult colon and intestine. The third principle component (PC3) accounts for 6.7% of cumulative variation and separates the samples according to regional identity, and shows that HCOs are more similar to colon whereas HIOs cluster with small intestine (FIG. 7A). Interestingly, human fetal samples did not cluster based on regional identity (small intestine vs colon)

suggesting that these samples may not have been cleanly isolated from the indicated region of the GI tract.

[00113] Applicant next used hypergeometric means test to determine the probability that HIOs and HCOs share similar patterns of region-specific gene expression small intestine and colon (FIG. 7B). A total of 341 transcripts are expressed in the small intestine and in NOGGIN treated HIOs as compared to colon or BMP2 treated HCOs, a proportion that is exceedingly unlikely by chance alone ($P = 1.5 \times 10^{-143}$). Similarly, the gene set that is up-regulated in the control HIOs shares a highly significant degree of similarity with the gene set up-regulated in adult small intestine relative to the adult colon ($P = 2.5 \times 10^{-203}$). Conversely, the gene set up-regulated in HCOs are highly enriched for genes that are up-regulated in the colon relative to the small intestine ($P = 4.1 \times 10^{-53}$ and $P = 6.0 \times 1073$, respectively). This analysis concluded that HIO patterning is most similar to human small intestine and HCO patterning is colonic. To further explore the nature of HIOs (NOG and control treated) and HCOs, Applicant conducted differential expression analysis (adult small intestine vs. adult colon; HIOs vs. HCOs). Applicant generated 4-way scatter plot, which also demonstrated that a high proportion of genes up-regulated in the colon were also up-regulated in HCOs and the majority of genes up-regulated in the small intestine were also up-regulated in HIOs (FIG. 7C, Table 1). Lastly, analysis of biological processes that were enriched revealed that adult colon and transplanted HCOs have highly active Wnt signaling and a similar HOX code (FIG. 7D). Taken together, these data suggest Applicant has developed a robust method to differentiate PSCs into human colonic tissue.

[00114] Table 1. Genes upregulated in adult small intestine and colon which are also upregulated in HIOs and HCOs respectively. Column 1, Commonly upregulated in NOG HIOs vs HCOs & adult small intestine vs adult colon, Column 2, Commonly upregulated in Control HIOs vs HCOs & adult small intestine vs adult colon, Column 3, Commonly upregulated in HCOs vs NOG HIOs & adult colon vs

adult small intestine, Column 4, Commonly upregulated in HCOs vs Control HIOs & adult colon vs adult small intestine

ABCA4	AADAC	AAGAB	AAK1
ABCC2	ABCA4	ABCA12	ABHD10
ABCC6	ABCB8	ACTR2	ABHD17C
ABCD1	ABCC10	ADAM10	ABL2
ABCG8	ABCC6	ADAM22	ACTR2
ABHD14A, ABHD14A-ACY1,ACY1	ABCD1	AGPS	ACVR2B
ABHD6	ABCG5	AGTPBP1	ACYP1
ACBD4	ABCG8	AKAP13, MIR7706	ADAM10
ACO2	ABHD14A, ABHD14A-ACY1, ACY1	ALDH1B1	ADAM17
ACOT11	ABHD16A	ALG5	ADAM22
ACP2	ABHD4	ANKDD1B	ADGRF4
ACSL5	ABHD6	ANKRD30BP2	AEBP2
ACY3	ACACB	ANTXR2	AGPS
ADAMTSL5	ACADS	ANXA3	AHI1
AGPAT3	ACADVL	ARFGEF3	AIDA
AKR1B10	ACKR4	ARHGAP44	AIFM3
AKR1C1	ACO2	ARPC5	AKAP11
AKR1C3	ACOT11	ASCC1	AKAP13,MIR7706
ALDOB	ACOT7	ASIP	AKAP5
ALPI	ACOX2	ATF6	ALG8
ANGPTL4	ACP2	ATOH1	ANKDD1B
ANXA13	ACSL5	ATXN3	ANKFY1
APOA1	ACTN4	B3GALNT2	ANKS1B
APOA1-AS	ACY3	B3GNT6	ANP32B
APOA4	ADAMTSL5	B4GALNT3	ANTXR2
APOBEC1	ADGRG4	BCAS1	AP2B1
APOBEC2	ADGRG5	BCL10	AP3M1
APOC2,APOC4, APOC4-APOC2	AGMO	BCLAF1	APH1B
APOC3	AGPAT1,MIR6721	BEND3	APOBR
APOL2	AGPAT2	BEST2	ARFGEF3
AQP3	AGPAT3	BTBD3	ARFIP1
AQP7	AK2	BZW1	ARL14EP
AQP7P1	AKR1A1	C11orf58	ARMC8
ATG4D	AKR1B10	C12orf75	ARPC5
AVIL	AKR1C1	CA12	ARRDC3
BAK1	AKR1C3	CAMSAP1	ASB7
BCRP3	AKR1C4	CAPN2	ASPH
BRE-AS1,RBKS	AKR7A3	CAPRIN1	ATG4C
BTD	ALDH1A3	CASC18	ATL3

BTNL3	ALDH2	CBFB	ATM
BTNL8	ALDOB	CCPG1,DYX1C1,DYX1C1-CCPG1	ATP13A3
C10orf25	ALPI	CD24	ATP2A3
C10orf67	AMBRA1	CD9	ATR
C11orf24	ANAPC2	CDC23	ATRX
C11orf86	ANGPTL4	CEACAM6	ATXN1
C19orf66	ANPEP	CEP290	ATXN3
C1orf115	ANXA13	CFC1,CFC1B	B3GALNT2
C1orf116	ANXA4	CLIC4	B3GNT6
C5orf56	AP5B1	CLMN	BAG5
C6orf132	APOA1	CLNS1A	BAZ1B
C6orf136	APOA1-AS	CLSTN1	BBIP1
C8G	APOA4	CNTN3	BCAS1
C9orf173	APOBEC1	CSRNP3	BCAT1
CA13	APOBEC2	DAAM1	BCLAF1
CALM3	APOC2,APOC4,APOC4-APOC2	DDX50	BEND3
CAMKK2	APOC3	DGKH	BEST2
CAPN10-AS1	APOL2	DICER1	BIN1
CAPN3	APOM	DIP2B	BMPR2
CASP1	AQP3	DMTN	BNC2
CATSPER2	AQP7	EARS2	BTBD10
CBR1	ARHGEF16	EBPL	BTBD3
CCL11	ASAH2	EEA1	BTBD7
CCL25	ASB13	EHF	BTF3L4
CD82	ASIC2	EPHA10	BTRC
CDCA3	ASPA	EPHB4	BZW1
CDH4	ATG4D	EXOC5	C10orf99
CDIP1	ATP11A	EXOC6	C11orf58
CDR2L	ATP5SL	FAM105A	C18orf54
CERK	ATXN2L	FAM169A	C3orf52
CES2	AZGP1	FAM175A	C7orf60
CGREF1	B3GNT8	FAM218A	CA12
CHRM4	BAG6	FAM60A	CA4
CIB2	BAIAP2L2	FAS	CAMK1D,LOC283070
CIDEB	BAIAP3	FECH	CAMSAP2
CIDEC	BAK1	FERMT1	CAPN8
CLDN15	BET1L	FFAR4	CAPZA1
CMTR1	BLNK	FGF7	CASC4
CNNM3	BRE-AS1,RBKS	FKTN	CASD1
CPS1	BTD	FMN2	CBFB
CRAT	BTNL3	FRMPD3	CBX5,MIR3198-2
CREB3L3	BTNL8	G3BP1	CCDC132
CRIP3	BUD13	GARS	CCDC88A
CTD-3080P12.3	C10orf54	GCSH	CCND1
CYP27A1	C11orf24	GGH	CCNJL

CYP2B7P	C11orf86	GJB4	CCNT1
CYP2C9	C15orf62	GLIS3	CD24
CYP2S1	C16orf58	GLUL	CD59
CYP3A5	C17orf78	GMNN	CD9
CYTH2	C18orf8	GNE	CDC42
DBP	C19orf12	GNPTAB	CDHR1
DCAF11	C19orf54	GOT2	CDK19
DECR1	C1orf116	GP9	CEACAM5
DGAT1,MIR6848	C2CD2L	GRSF1	CEACAM6
DGAT2	C5orf56	GSPT1	CEBPZ
DGKA	C6orf132	GYG2	CELF2
DHDH	C6orf136	HDAC1	CENPO
DHRS1	C8G	HIATL1	CEP250
DHRS11	CALCOCO1	HK2	CHD9
DHX16	CALM3	HMGA2	CHIC1
DMBT1	CAMK2G	HN1L	CLIC4
DNAJC22	CAMTA2	HNMT	CLMN
DNASE1	CAPN1	HNRNPAB	CLNS1A
DNPEP	CAPNS1	HOXA10-AS	CLTC
DOLPP1	CARD10	HOXA10,HOXA10-HOXA9,HOXA9	CMTM6
DOT1L	CARD6	HOXA11	CNEP1R1
DTX1	CASP1	HOXB9	CNTN3
ELMOD3	CASP4	HOXB-AS3	CPM
EMB	CASP9	IARS	CRK
ENKUR	CBLC	IFT74-AS1	CRYM
EPHX2	CBR1	IL1R2	CSNK1A1
ERICH4	CC2D1A	ILDR1	CSRNP3
ESPN	CCL25	IPO5P1	CTDSPL
ETV7	CD302,LY75,LY75-CD302	IQGAP1	CTTNBP2NL
EXOC3L4	CD68	ITM2C	CYLD
F10	CD74	JAG1	CYP20A1
FAM102A	CD82	JPH1	DAAM1
FAM109A	CDC42BPB	KCNJ2	DCBLD2
FBP1	CDC42EP4	KCNN4	DCP2
FBXO7	CDCA3	KCNRG,TRIM13	DDX50
FCHSD1	CDHR5	KCTD1	DDX6
FLJ12825	CDIP1	KCTD20	DGKH
FLJ22763	CDK18	KLK15	DHRS13
FUOM	CDK2	KNOP1	DHRS9
FXR2	CDK20	KPNA4	DHX57
GABRE	CDR2L	LEFTY1	DICER1
GALK1	CEACAM18	LIMK2	DIO3OS
GALT	CELA3A	LINC00341	DISC1,TSNAX,TSNAX-DISC1
GATA4	CENPV	LINC00858	DNAJC3
GATA5	CERS2	LIPH	DNAL1

GATS	CES2	LOC100507346	DPY19L1
GCHFR	CFI	LOC101928233	DSEL
GIGYF1	CFL1	LOC101929395	DSTYK
GNA11	CGREF1	LOC101929524	DTD2
GOLT1A	CHP2	LRRK1	EBPL
GOSR2	CHRM4	MAML2	EED,MIR6755
GPD1	CIAO1	MAPRE2	EFNA5
GPRIN1	CIB2	MARCH3	EHF
GRAMD1B	CIDEB	MARCKSL1	EI24
GRIA1	CIDEC	MBNL3	EID1
GSDMB	CISD1	MCOLN2	EIF4E
GSK3A	CLDN15	MECOM	EIF5B
GSTK1	CLDN18	METTL5	EMC1
HADHA	CLPTM1	MFAP3L	ENAH
HAGH	CMBL	MFHAS1	ENDOD1
HAPLN4	CNNM3	MINA	ENTPD1
HEBP1	CNPY2,PAN2	MLLT3	EPAS1
HOPX	COASY	MPHOSPH6	ERCC6L2
HOXA4	COMMD9	MPLKIP	ERMP1
HPS1	COMT,MIR4761	MPZL2	ERN2
IDH3A	CPA2	MREG	EXOC2
IFIT3	CPPED1	MRPL1	EXOC4
IGSF23	CRADD	MRPL3	EXOC5
IL2RB	CRAT	MTL5	EXOC6
INTS12	CREB3L3	MYO3A	FAM102B
IRF1	CRELD1	MYO5C	FAM103A1
IRF8	CS	NAA15	FAM105A
ISG20	CSK	NAP1L1	FAM120A
ITPK1	CTSO	NCBP1	FAM13B
KDM2A	CXCR3	NDC1	FAM169A
KDM6B	CYB5A	NEDD4L	FAM178A
KDM8	CYP27A1	NEURL1B	FAM208A
KHK	CYP2C19	NLE1	FAM46A
KIAA2013	CYP2S1	NOLC1	FAM83H-AS1
KIFC3	CYP3A4	NOTCH1	FAM8A1
KLC4	CYSLTR2	NOTCH2	FAM98B
LBX2-AS1	DBP	NRARP	FANCI
LINC00574	DCAF11	NRXN1	FAR2P2
LINC01268	DECR1	NSF,NSFP1	FBXO28
LOC100240735	DEDD	NT5DC3	FBXO45
LOC284825	DEGS2	NUDT4	FCF1
LOC646471	DERA	NXPE1	FEM1B
LOC728989	DESI1	NXPE2	FEM1C
LPCAT3	DFNA5	NXPE4	FFAR4
LPIN3	DGAT1,MIR6848	ODC1	FKBP5,LOC285847
LRRC75A	DGAT2	ORC5	FKTN
LRRC75B	DGKA	P4HA1	FLOT2
MALL	DGKG	PAPPA2	FNDC3B

MAPKBP1	DGKQ	PARM1	FOCAD
METTL7B	DGKZ	PAWR	FOXD2
MFSD2A	DHDH	PCDHB11	FOXO3
MGAM	DHRS11	PDE3B	FOXO3B,ZNF286B
MICALL2	DHRS7	PDZK1IP1	FRMPD3
MICU1	DHX16	PGBD5	FRYL
MIR1268A,SLC27A4	DMBT1	PHF20	FSIP2
MIR22,MIR22HG	DNAJC22	PHF6	FZD4
MIR31HG	DNASE1	PKIB	G3BP1
MIR3615,SLC9A3R1	DNPEP	PLCD3	GGH
MIR5187,TOMM40L	DOLPP1	PLSCR4	GIN1
MIR5193,UBA7	DPP9	POF1B	GJC1
MIR6073,SOX6	DSCR3	POLR3B	GLB1L2
MIR621,SLC25A15	DTX1	POSTN	GLG1
MIR7703,PSME2	E2F4	PP14571	GLIS3
MISP	EGFR-AS1	PPIC	GLTSCR1L
MME	EIF6	PPP1R8	GLUL
MMEL1	ENPP6	PPP2R3A	GMNN
MOCS1	EPB41L3	PPP3CA	GNAI1
MOGAT3	EPHA1	PREP	GNAQ
MON1A	EPHB1	PRKACB	GNE
MS4A8	EPHX2	PRKAR2A	GOLGA3
MSRA	EPS8L2	PRKRIR	GOPC
MST1	EPSTI1	PRMT5	GP9
MTTP	ERAL1	PSMD6	GPC6
MUS81	ERF	PSME4	GPX8
MYO15B	ESPN	PTAR1	GRM7
MYO1A	ESRRA	PTTG1IP	GRSF1
NAGS	ETV3	PUM1	GTF2F2
NELL2	ETV7	PYGL	GTF3C1
NGEF	EWSR1	QPCT	HABP4
NOP9	EXOC3L4	R3HDM1	HEATR3
NPC1L1	F10	RAB3B	HIATL1
NR0B2	FABP2	RABEP1	HMG20A
NR1I3	FAH	RAP1GDS1	HMGA2
NSUN6	FAM101A,ZNF664,ZNF664-FAM101A	RAPGEF2	HN1L
NUB1	FAM102A	RBMS3	HOXA10-AS
OGDH	FAM109A	RCC2	HOXA10,HOXA10-HOXA9,HOXA9
OTC	FAM32A	REXO2	HOXB5
P4HB	FAM83G	RIF1	HOXB6
PARP12	FBLIM1	RIMS3	HOXB7
PARP3	FBP1	RNASEH2B	HOXB8

PATL2	FLJ22763	RPA2	HOXB9
PCK2	FUOM	RSF1	HOXB-AS3
PCSK5	FZR1	RSL24D1	IFFO2
PDLIM2	GABRA4	RXFP4	IFNAR1
PDZD7	GAL3ST1	SATB2	IFT74-AS1
PDZK1	GALK1	SATB2-AS1	IGF1R
PEBP1	GALNT6	SCLT1	IGIP
PEPD	GALT	SERBP1	IL17RD
PEX14	GATA4	SETBP1	IL1R2
PGRMC2	GATA5	SH3PXD2A-AS1	IL20RB
PHEX	GCNT4	SIPA1L2	IL6ST
PKLR	GFI1B	SLC16A9	ILDR1
PLA2G6	GGT1	SLC1A3	IMPAD1
PLCB3	GLOD5	SLC39A8	INPP5F
PLEKHS1	GLRX	SLC7A2	IPO11,IPO11-LRRC70,LRRC70
PLIN2	GLYCTK	SLC9A2	IPO5
PLIN3	GNA11	SLCO4A1-AS1	IPO5P1
PLLP	GNB1	SMAD5	IPO7
PNP	GOLT1A	SMARCA5	IQGAP1
PP7080	GOSR2	SMC6	ITGAV
PQLC2	GPD1	SNRPE	ITGB1
PRAP1	GPR108	SNX13	ITM2A
PRDM7	GPR35	SOCS5	ITPRIPL2
PRODH	GRAMD1B	SORBS2	JAG1
PSMB9	GRIA1	SPAG1	JPH1
PSMD9	GRK5	SRSF12	KBTBD6
PSME1	GRTP1-AS1	SRSF9	KCNJ2
PTPRH	GSDMB	ST6GAL2	KCNN4
PXDC1	GSK3A	STAB2	KCNRG,TRIM13
RAB11FIP3	GSTA1	STMND1	KCTD10
RAB17	GSTA2	STS	KCTD20
RAB5C	GSTK1	STX19	KDM5B
RAB8A	GSTM4	SUSD1	KIAA0226L
RARRES3	GTF2I	SUV39H2	KIAA0232
RBP2	GTPBP1	TBL2	KIAA0513
REEP6	GUCD1	TCTA	KIAA1143
REG1A	HADHB	TDGF1	KIAA1429
RPS6KA1	HAGH	TFRC	KIAA1715
RTKN	HAPLN4	TMA16	KLHL15
RTP4	HDAC6	TMCC1-AS1	KLK15
SAT1	HDGF	TMED10	KPNA4
SAT2	HDHD3	TMED2	KRR1
SCAMP5	HEBP1	TMEM123	LAPTM4A
SCNN1D	HECTD3	TMEM159	LARS
SCRN2	HIP1R	TMEM200B	LEFTY1
SDHA	HLA-F	TMEM38A	LIFR
SEC14L2	HMGA1	TRABD2A	LIMD1

SERP2	HNF1A	TSN	LIMK2
SFRP5	HNF4A-AS1	TSPAN5	LINC00341
SFXN3	HOPX	TTC3	LINC00482
SH3BP1	HPS1	TTC8	LINC00515
SH3GL1	HRASLS2	TTPA	LINC00657
SHBG	HRH2	UBE2A	LINC01006
SIDT2	HSD3B7	UBE2N	LMAN2L
SLC12A7	HYKK	UGP2	LOC100129550
SLC15A1	IDNK	UNC13B	LOC100507351
SLC1A7	IFIT3	URB1	LOC101929374
SLC22A4	IFNLR1	VWA3B	LOC101929524
SLC23A1	IGSF23	WDHD1	LOC105372441
SLC25A20	IL22RA1	WDR35	LOC731424
SLC25A34	IL2RB	WDR78	LOC93622
SLC25A44	ILVBL	WIPI1	LRCH2
SLC25A45	IMMP2L	WNK4	LRRC37A4P
SLC26A11	INPP5J	WWP1	LRRC58
SLC2A2	INTS12	XPO4	LUZP6
SLC35B1	IQSEC2	YWHAE	LYST
SLC37A4	IRF1	ZBTB7C	MAFA
SLC39A5	ISG20	ZBTB8B	MAGEF1
SLC3A2	ITM2B	ZFHX3	MAGT1
SLC52A1	ITPK1	ZNF658	MAL2
SLC5A1	ITPKA	ZNF774	MAP3K7
SLC5A9	KALRN	ZNF780B	MARCKS
SLC6A19	KDF1		MATR3,SNHG4
SLC6A20	KDM6B		MBNL2
SLC7A7	KDM8		MBNL3
SMIM24	KHK		MBOAT2
SMIM5	KIAA0141		MBTPS2
SMLR1	KIAA1551		MDN1
SMPD3	KIAA2013		MECOM
SOWAHA	KLC4		METTL8
SPNS3	KLHDC8B		MFAP3L
ST7,ST7-OT3	LASP1		MFSD4
STRC	LBX2-AS1		MFSD6L
SULT1A1	LEAP2		MIB1
SULT1A2	LHPP		MIER1
SYK	LINC00319		MIOS
SYP	LINC00330		MIR1244-4,PTMA
TAP2	LINC00483		MIR4680,PDCD4
TCF7	LINC00574		MIR6824,SLC26A6
TICAM1	LINC00667		MLF1
TKFC	LINC01137		MLLT3
TM4SF20	LINC01347		MLXIP
TM4SF4	LIPE		MMGT1
TM4SF5	LIPT1		MOB1B
TM6SF2	LMBR1L		MON2

TMEM150B	LOC100093631		MORF4L1
TMEM184A	LOC100506302		MPZL1
TMEM253	LOC100507334		MREG
TMEM37	LOC101927051		MRPL1
TMEM41A	LOC284825		MRPS6,SLC5A3
TMEM82	LOC90768		MTHFD2
TMEM86B	LPCAT3		MTMR6
TNFRSF14	LRP5		MTSS1
TNFRSF1A	LRRC28		MTURN
TNRC6C-AS1	LRRC41		MUC1
TOM1	LRRC66		MUC12
TREH	LRRC75A		MYO3A
TRIM15	LSMEM2		MYO5C
TRIM50	LYRM5		NAA15
TTC31	LZTS3		NAA50
TTC38	MALL		NAP1L1
			NBPF10,NBPF12,NB
			PF20,NBPF25P,NBPF
UGT2B7	MAP2K3		8,NBPF9
UGT3A1	MAP3K11		NCBP1
USH1C	MAPK3		NCOA3
WBP2	MAPKAPK2		NDC1
WNT3	MAPKBP1		NEK1
XAF1	MARC2		NEURL1B
XDH	MBD1		NFIA
XPNPEP2	MCRS1		NFYB
ZMYND15	MCUR1		NIFK-AS1
ZNF300	MEP1A		NKIRAS1
ZSWIM8	MEP1B		NOL11
	METTL17		NOL9
	METTL7B		NOTCH1
	MFSD2A		NPAS1
	MGAM		NRXN1
	MGAM2		NSF,NSFP1
	MGAT3		NT5C2
	MGST3		NT5DC3
	MICAL1,ZBTB24		NUBPL
	MICU1		NUCKS1
	MIR1268A,SLC27A		
	4		NUDT4
	MIR22,MIR22HG		NUP133
	MIR3615,SLC9A3R1		NUP205
	MIR5187,TOMM40L		NUS1
	MIR5193,UBA7		NXPE1
	MIR639,TECR		NXPE4
	MIR7109,PISD		OPHN1
	MIR7703,PSME2		ORC5
	MISP		PARM1

	MLF2		PBRM1
	MLX		PCM1
	MLXIPL		PDE3B
	MME		PDE4D
	MMEL1		PDS5A
	MMP24		PDS5B
	MOCOS		PEAK1
	MOCS1		PGBD5
	MOGAT2		PGGT1B
	MOGAT3		PGM2L1
	MOGS		PHC3
	MON1A		PHF14
	MOV10		PHF20
	MPP1		PHF6
	MS4A8		PHIP
	MSRA		PHTF2
	MST1		PIAS2
	MST1R		PIBF1
	MTTP		PIGN
	MUC17		PIGX
	MYD88		PIK3R3
	MYO15B		PIKFYVE
	MYO19		PITHD1
	MYRF		PJA2
	NAALADL1		PKI55
	NAGS		PKIB
	NAPRT		PKNOX1
	NCK2		PLEKHF2
	NCSTN		PLXNA2
	NELL2		POF1B
	NGEF		POLR1E
	NIT1		POT1
	NLRP6		POU2F1
	NOL4L		PP14571
	NOP9		PPIC
	NPC1L1		PPIP5K2
	NPY6R		PPM1B
	NQO2		PPM1K
	NR0B2		PPP1R3B
	NR1H3		PPP2R5C
	NR1I3		PPP3CA
	NUCB1		PRKACB
	NUTM2B-AS1		PRKDC
	OCIAD2		PRKG1
	OGDH		PRKRIR
	OGG1		PRPS2
	OTC		PRRT3-AS1
	OXNAD1		PSME4

	P4HB		PTAR1
	PAOX		PTEN
	PARP2		PTGDR
	PARP3		PTPN14
	PBLD		PUM1
	PBX2		PURB
	PCBP2,PCBP2-OT1		PWWP2A
	PCK2		PYGB
	PCSK5		PYGO1
	PCYT1A		PYURF
	PDE8B		QPCT
	PDLIM2		RAB11FIP2
	PDSS1		RAB3B
	PDXP		RAB40B
	PDZD7		RABEP1
	PEBP1		RABGAP1
			RALGAPA1,RALGA
	PEPD		PA1P
	PEX14		RANBP2
	PEX16		RAP1GDS1
	PFKL		RAP2A
	PFKP		RAP2B
	PGD		RAPGEF6
	PGRMC2		RASA2
	PGS1		RASEF
	PIM1		RBFOX2
	PIP5K1A		RBM7
	PKLR		RBMS3
	PLCB3		RBPJ
	PLEK2		RBPMS-AS1
	PLEKHA7		RBSN
	PLEKHS1		RBX1
	PLIN3		RCC2
	PLLP		RDX
	PMM1		REXO2
	PNLIPRP2		RGL3
	PNP		RIF1
	POLR3H		RIMKLA
	POMGNT1		RLIM
	POR		RND3
	PP7080		RNF139
	PPIP5K1		RNF144A
	PPP2R5D		RNF145
	PPP6R1		RNF223
	PQBP1		RNMT
	PQLC2		RSL24D1
	PRAP1		RXFP4
	PRDX2		SAMD13

	PRKCD		SAR1A
	PRKCZ		SARAF
	PRKD2		SATB2
	PRODH		SATB2-AS1
	PRR13		SBNO1
	PRSS1		SCAI
	PRSS3P2		SCFD1
	PSD4		SDC4
	PSMA1		SEC22A
	PSMB10		SEC23IP
	PSMB8		SEC62
	PSMB9		SECISBP2L
	PSMD9		SEL1L
	PSME1		SEMA3C
	PTK2B		SEMA3D
	PTPRH		SEMA5A
	PVRL2		SEPT11
	PXDC1		SEPT7
	QRICH1		SERBP1
	RAB11FIP3		SERINC5
	RAB17		SERTAD2
	RAB5C		SESN1
	RAB8A		SESN3
	RARA		SETX
	RARRES3		SH3PXD2A-AS1
	RASSF4		SHOC2
	RBP2		SHROOM4
	REEP6		SIPA1L2
	REG1A		SLC10A7
	RFX5		SLC15A2
	RGN		SLC16A9
	RIC3		SLC19A2
	RIPK3		SLC1A3
	RIPK4		SLC22A15
	RMDN3		SLC25A12
	RMND1		SLC25A30
	RNF10		SLC2A10
	RNF123		SLC30A6
	RNF167		SLC35A1
	RRNAD1		SLC37A3
	RTKN		SLC38A2
	RTP4		SLC38A6
	SAPCD1-AS1,VWA7		SLC39A8
	SAT2		SLC44A1
	SCAMP5		SLC7A2
	SCARB1		SLC9A2
	SCML4		SMAD5

	SCNN1D		SMARCA5
	SCRN2		SMC6
	SDHD		SMG1
	SEC13		SMIM14
	SEC14L2		SNRPE
	SEC16B		SNX13
	SFRP5		SOCS5
	SFXN3		SORBS2
	SH3BP1		SPAG1
	SH3GL1		SPIN2B
	SHPK,TRPV1		SPIRE1
	SIDT2		SPTAN1
	SIGLEC12		SPTSSA
	SLC12A7		SRSF12
	SLC13A2		SSB
	SLC16A13		SSR1
	SLC16A5		SSR3
	SLC19A1		ST6GAL2
	SLC22A18		ST7L
	SLC22A4		STAB2
	SLC23A1		STAG1
	SLC25A20		STMND1
	SLC25A44		STRN3
	SLC25A45		STS
	SLC25A5		STX19
	SLC26A11		STX6
	SLC2A12		SUMF1
	SLC2A5		SUPT16H
	SLC2A9		SUV39H2
	SLC35B1		SYT7
	SLC37A4		SYTL2
	SLC39A5		SYTL4
	SLC3A2		TACC1
	SLC52A1		TAF9B
	SLC5A1		TAOK1
	SLC5A6		TBL1X
	SLC6A19		TCAM1P
	SLC6A20		TDGF1
	SLC7A7		TEAD1
	SLC7A9		TFCP2L1
	SLC9A3		TFRC
	SLX4		TGFBR1
	SMAD3		THADA
	SMARCD1		TICAM2,TMED7,TMED7-TICAM2
	SMIM24		TINCR
	SMLR1		TLK1
	SMOX		TLN2

	SMPD3		TMCC1-AS1
	SOAT2		TMED10
	SPANXN3		TMED9
	SPHK2		TMEM106B
	SPNS3		TMEM123
	SRC		TMEM159
	SSTR1		TMEM194A
	ST7,ST7-OT3		TMEM194B
	STAT6		TMEM2
	STAU1		TMEM44
	STK24		TMEM45A
	SUCLG1		TMEM87A
	SULT1A1		TMX1
	SULT1A2		TNFRSF10D
	SULT2A1		TNKS
	SYP		TNRC6C
	TAP2		TOP2B
	TBK1		TP53BP1
	TCF7		TP53INP1
	TFG		TRABD2A
	THRA		TRIM23
	TIAM2		TRIM37
	TICAM1		TRIP12
	TJAP1		TRMT5
	TKFC		TROVE2
	TLDC2		TSN
	TM4SF4		TSPAN5
	TM4SF5		TSPAN6
	TM6SF2		TSPYL4
	TMED4		TTC28
	TMEM116		TTC3
	TMEM120A		TTL
	TMEM139		TTPA
	TMEM150B		TTPAL
	TMEM177		TWISTNB
	TMEM184A		TWSG1
	TMEM229B		TXNDC15
	TMEM253		UBE2D1
	TMEM25,TTC36		UBE2Q2
	TMEM37		UBR5
	TMEM51		UGGT1
	TMEM51-AS1		UGGT2
	TMEM82		UNC5C
	TMEM86B		USP13
	TMEM92		USP24
	TNFRSF14		USP34
	TNFRSF1A		USP47
	TNIK		USP53

	TOM1		UXS1
	TOM1L1		VANGL1
	TOX4		VKORC1L1
	TPI1		VOPP1
	TRAF4		VPS13B
	TREH		VPS13C
	TRIM14		WAC-AS1
	TRIM15		WBP5
	TRIM16		WDFY1
	TRIM21		WDHD1
	TTC38		WDR36
	UBXN2A		WDR7
	UGT3A1		WDR78
	UNC5CL		WDR89
	USF1		WNK4
	USH1C		XIAP
	USP10		XPNPEP3
	USP2		XPO4
	VRK3		YTHDF3
	VRTN		ZBTB10
	WBP2		ZBTB7C
	WDR45		ZDHHC7
	WDTC1		ZFHX3
	WNT3		ZFP90
	WWC1		ZFX
	XAF1		ZMAT2
	XDH		ZMPSTE24
	XPNPEP1		ZMYM4
	ZDHHC9		ZNF148
	ZER1		ZNF260
	ZFAND3		ZNF264
	ZFYVE27		ZNF320
	ZMYND15		ZNF555
	ZNF384		ZNF644
	ZNF782		ZNF652
	ZRANB2-AS1		ZNF678
	ZSWIM8		ZNF69
			ZNF704
			ZNF709
			ZNF766
			ZNF780B
			ZNF81
			ZYG11B

[00115] DISCUSSION

[00116] Historically, the classification of foregut, midgut, and hindgut are based on the development of the anterior and posterior intestinal portals and the source of mesenteric blood supply (Uppal et al., 2011). An alternative definition of midgut and hindgut have been proposed, in which the midgut is the portion of the intestine derived from the portion anterior to the umbilicus and the hindgut derives posterior to the umbilicus (Johnston, 1913; Savin et al., 2011). In either case, the historic reliance on anatomical landmarks, and lack of more precise molecular markers to distinguish fore, mid and hindgut, have made it difficult to develop methods to generate these cell/tissues in vitro from PSCs. Therefore, identification of markers that clearly demarcate regions of developing mid and hindgut is essential.

[00117] Applicant used a combination of CDX2, GATA4, ONECUT1 and SATB2 to identify that distinct molecular boundaries are established at early stages of mid and hindgut development in Xenopus, mouse and humans. Interestingly, GATA4 and SATB2 expression domains form a boundary at the yolk stalk/presumptive umbilical cord in mice, and this boundary is maintained throughout development and in the adult intestine. The fact that GATA4 expression marks the intestine anterior to the umbilicus, and SATB2 expression marks the domain posterior to the umbilicus, suggests that the umbilicus is the boundary between the midgut and hindgut (Johnston, 1913; Savin et al., 2011).

[00118] While ONECUT1 expression in HIOs and SATB2 expression is HCOs is consistent with their proximal and distal identify respectively, GATA4 was not as robustly expressed in proximal HIOs in vitro as would be expected given its embryonic expression (data not shown). In contrast, GATA4 was robustly expressed following in vivo maturation of HIOs and in enteroids generated from patient biopsies (data not shown). This could suggest that factors involved in expression of GATA4 are absent in culture conditions or that maturation in vivo is required for epithelial expression of GATA4. This data also suggests that high levels of GATA4 expression may be dispensable for early regionalization of the intestine, consistent with intestinal Gata4 knockout mice that retain normal Onecut factor expression (Battle et al., 2008).

In addition, a small subset of BMP treated organoids lost CDX2 expression and activated expression of the bladder markers Keratin 13 and Uroplakin 1a (data not shown). This is consistent with BMP organoids having a hindgut fate since urothelial tissue is derived from the hindgut/cloaca (Georgas et al., 2015).

[00119] SATB2 is expressed throughout development of the distal ileum and large intestine, however it is not known if SATB2 is required for development of the distal intestine. Mouse knockout studies have focused on craniofacial and cortical neuronal development since mutations in SATB2 has been implicated in Cleft Palate associated with 2q32-q33 deletions and Glass Syndrome (FitzPatrick et al., 2003). However, there is indirect evidence that SATB2 may play a role human colonic physiology. SATB2 has been identified in Genome Wide Association Studies as an ulcerative colitis susceptibility gene (McGovern et al., 2010). In addition, loss of SATB2 expression has been shown to be associated with poor prognosis in colorectal cancer patients (Eberhard et al., 2012). Future studies with HCOs may allow identification of SATB2 targets in the developing colon, which could provide insight into the pathology of ulcerative colitis and colorectal cancer.

[00120] Several studies in model organisms have implicated the BMP signaling pathway in patterning endoderm during hindgut development (Kumar et al., 2003; Roberts et al., 1995; Sherwood et al., 2011; Tiso et al., 2002; Wills et al., 2008). Consistent with this, Applicant has demonstrated that posterior patterning of human definitive endoderm is dependent on BMP signaling, as inhibition of BMP abrogates the ability of WNT and FGF to promote a posterior endoderm fate (McCracken et al., 2014). However, it is not surprising that BMP signaling plays other temporally distinct roles during intestinal development. For example, after the establishment of proximal-distal regional domains, BMP signaling functions to establish the crypt-villus axis in the intestine and colon (Li, 2005). Thus, a temporal requirement for patterning allows the embryo to use the same signaling pathway for multiple purposes gut development, as has been reported in Drosophila midgut (Driver and Ohlstein, 2014; Guo et al., 2013). In a human disease context, mutations in BMPR1A are associated with a subset of

patients with Juvenile Polyposis Syndrome. The HCO system was highly amenable for identifying the HOX code that is downstream of BMP during early development and it could be interesting to determine if hamartomatous polyps with BMPR1A mutations have altered HOX gene expression.

[00121] Applicant previously reported the in vitro directed differentiation and in vivo transplantation of HIOs (Spence et al., 2011; Watson et al., 2014), which were small intestinal. Given the unique physiology and pathological conditions that affect the large intestine, it was imperative to develop a colonic model system to interrogate pathophysiological questions specific to the colon. Developmentally, this system provides the opportunity to investigate fundamental questions about how regional identity is established. HIOs and HCOs develop unique cell types, such as Paneth cells in the HIOs and colon-specific goblet cells in HCOs. Moreover, HIOs and HCOs have a distinct set of EECs that are normally enriched in the small and large intestine, respectively. Regionalized organoids should provide a platform for future studies of how different regions of the intestine give rise to regionalized stem cells. In addition, generation of HCOs will allow for modeling of diseases that affect the colon such as ulcerative colitis and colorectal cancer.

[00122] Materials and Methods

[00123] Animals. Immune-deficient NOD-SCID IL-2Rynu" (NSG) mice, 8-16 weeks old, were used in transplantation experiments (obtained from the Comprehensive Mouse and Cancer Core Facility, Cincinnati, Ohio). Wild type mice were used for studies on mouse fetal intestine. All mice were housed in the animal facility at the Cincinnati Children's Hospital Medical Center (CCHMC). All experiments were performed with the approval of the Institutional Animal Care and Use Committee of CCHMC.

[00124] BMP inhibition in frog and mouse embryos. Xenopus tropicalis embryo culture and small molecule treatments were performed as previously described (Rankin et al., 2012; Rankin et al., 2015). DMH-1 (Sigma D8946) was dissolved in

DMSO, and used at final concentration of 20 pM; equal concentrations of DMSO vehicle were used on sibling embryos. Inhibitor treatment experiments were repeated twice with similar effects on the markers analyzed. For Xenopus in-situ hybridization analyses, DIG-labeled antisense RNA probes were generated using linearized full-length cDNA plasmid templates (X.tropicalis satb2 was purchased from ATCC, clone 7720194; HinDIII, T7 for probe; X.laevis satb2 was a gift for Tyler Square and Daniel Medeiros, University of Colorado-Boulder; Xbal, Sp6 for probe).Complete details describing probe synthesis and the in-situ hybridization protocol are available on Xenbase (hftp://wiki.xenbase.orq/xenwiki/index.php/Protocols).

[00125] For mouse whole embryo cultures, e7.5 embryos were cultured in a 1:1 mixture of Ham's F12 medium and whole embryo culture rat serum (Harlan Labs) containing N-2 Supplement (Invitrogen). Vessels were placed on a roller culture apparatus (BTC Engineering, Cambridge, UK) and maintained for 2 days at 37° C and gassed with 20% 02 and 5% CO2. BMP signaling was inhibited by treatment with 5 pM DMH-1, with DMSO serving as a vehicle control.

[00126] Generation of human midgut/hindgut spheroids. Human intestinal organoids were generated and maintained as previously described (Watson et al., 2014). Human embryonic stem cells and induced pluripotent stem cells were grown in feeder-free conditions in six-well Nunclon surface plates (Nunc) coated with Matrigel (basement membrane matrix, BD Biosciences) and maintained in mTESR1 media (Stem Cell Technologies). For induction of definitive endoderm (DE), human ES or iPS cells were passaged with Accutase (Invitrogen) and plated at a density of 100,000 cells per well in a Matrigel-coated, Nunclon surface 24-well plate. For Accutase split cells, 10 pM Y27632 compound (Sigma) was added to the media for the first day. After the first day, media was changed to mTESR1 and cells were grown for an additional 24 hours. Cells were then treated with 100 ng/mL of Activin A for 3 days as previously described (Spence et al., 2011). DE was then treated with hindgut induction medium (RPMI 1640, 2 mM L-glutamine, 2% decomplemented FBS,

penicillin-streptomycin and 100 ng/mL Activin A) for 4 d with 500 ng/mL FGF4 (R&D) and 3 pM Chiron 99021 (Tocris) to induce formation of mid-hindgut spheroids.

[00127] Patterning midgut/hingut spheroids into HIOs and HCOs. Spheroids were collected from 24 well plate and plated in Matrigel (BD). To generate proximal HIOs, spheroids were overlayed with intestinal growth medium (Advanced DMEM/F-12, N2, B27, 15 mM HEPES, 2 mM L-glutamine, penicillin-streptomycin) supplemented with 100 ng/mL EGF (R&D) alone, or 100 ng/mL EGF with 100 ng/ml NOGGIN (R&D). To generate HCOs, spheroids were overlayed with 100 ng/mL EGF plus 100 ng/mL BMP (R&D). For SHH experiments, 1 pM SAG (Tocris), 5 pM SAG or 2.5 pM Cyclopamine (Tocris) were added to control media for initial 3 days after which RNA samples were collected. Media was changed at 3 days with only EGF being maintained in the media for all patterning conditions. Media was then changed twice weekly thereafter. HIOs and HCOs were replated in fresh Matrigel every 14 days.

[00128] Generation of NEUROGENIN3 inducible line. To generate a doxycycline inducible NEUROG3 line, Applicant transduced IPSC 72.3 cells with pINDUCER21-NEUROG3 lentivirus and selected using 250 g/mL of G418. Both the IPSC 72.3 cell line and the inducible NEUROG3 have been described previously (McCracken et al., 2014). Stably transduced cells were differentiated into mid/hindgut spheroids and then patterned into HIOs or HCOs. Spheroids were grown for 28 days and were pulsed with 0.5ug/mL of doxycycline for 8 hrs. At day 35, organoids were collected and were analyzed by QPCR and IF.

[00129] Growth of organoid mesenchyme. Mesenchymal cells from organoids which attach to the bottom of the 24-well plate attach and grow in 2 dimensions. To expand mesenchymal cells from organoids, DMEM 10%FBS + L-glutamine +penicillin-streptomycin was added to wells from which organoids had been harvested at 14 days. Media was changed twice weekly for a total of 2-3 weeks until near 100% confluence was achieved.

[00130] Transplantation of human intestinal organoids. NSG mice were kept on antibiotic chow (275 p.p.m. Sulfamethoxazole and 1,365 p.p.m. Trimethoprim; Test Diet). Food and water was provided ad libitum before and after surgeries. A single HIO, matured in vitro for 28 days, was removed from Matrigel, washed with cold phosphate-buffered saline (DPBS; Gibco), and embedded into purified type I collagen (rat tail collagen; BD Biosciences) 12 hours before surgery to allow for formation of a solidified gel plug. These plugs were then placed into standard growth media overnight in intestinal growth medium (Advanced DMEM/F-12, B27, 15 mM HEPES, 2 mM L-glutamine, penicillin-streptomycin) supplemented with 100 ng/mL EGF (R&D). HIOs were then transplanted under the kidney capsule as previously reported (Watson et al., 2014). Briefly, the mice were anesthetized with 2% inhaled isoflurane (Butler Schein), and the left side of the mouse was then prepped in sterile fashion with isopropyl alcohol and povidine-iodine. A small left-posterior subcostal incision was made to expose the kidney. A subcapsular pocket was created and the collagen-embedded HIO was then placed into the pocket. The kidney was then returned to the peritoneal cavity and the mice were given an IP flush of Zosyn (100 mg/kg; Pfizer Inc.). The skin was closed in a double layer and the mice were given a subcutaneous injection with Buprenex (0.05 mg/kg; Midwest Veterinary Supply). At 8-10 weeks following engraftment, the mice were then humanely euthanized or subjected to further experimentation.

[00131] Tissue processing, immunofluorescence and microscopy. Tissues were fixed for 1-3 hours in 4% paraformaldehyde (PFA) on ice depending on the size of the tissue. Organoids and transplant engraftments were frozen in OCT. OCT sections were blocked using donkey serum (5% serum in 1X PBS plus 0.5% Triton-X) for 30 min and incubated with primary antibody overnight at 4 °C. Slides were then washed 3X with 1X PBS plus 0.5% Triton-X and incubated in secondary antibody with DAPI in blocking buffer for 2 h at room temperature. See Table 2 for a list of antibodies and respective dilutions. Slides were then washed 2X with 1X PBS plus 0.5% Triton-X followed by a final wash in 1X PBS. Coverslips were then mounted using Fluoromount-G® (SouthernBiotech). Images were captured on a Nikon Al confocal

microscope and analyzed using Imaris Imaging Software (Bitplane). For whole-mount staining, tissues were processed similarly as above and then cleared in Murray's solution. Imaging was performed with a Nikon Al confocal microscope.

[00132] Table 2. QPCR primers used. See FIGS 3 and 4.

GENE	Sequence
CDH1 FWD	GACCGGTGCAATCTTCAAA
CDH1 REV	TTGACGCCGAGAGCTACAC
CHGA FWD	TGTGTCGGAGATGACCTCAA
CHGA REV	GTCCTGGCTCTTCTGCTCTG
CKB FWD	CCCACACCAGGAAGGTCTTA
CKB REV	CCTCTTCGACAAGCCCGT
FXYD3 FWD	AGGGTCACCTTCTGCATGTC
FXYD3 REV	CTTCGGATAAACGCAGGACT
GATA4 FWD	TAGCCCCACAGTTGACACAC
GATA4 REV	GTCCTGCACAGCCTGCC
HOXA13 FWD	GCACCTTGGTATAAGGCACG
HOXA13 REV	CCTCTGGAAGTCCACTCTGC
HOXB13 FWD	GCTGTACGGAATGCGTTTCT
HOXB13 REV	AACCCACCAGGTCCCTTTT
HOXD13 FWD	CCTCTTCGGTAGACGCACAT
HOXD13 REV	CAGGTGTACTGCACCAAGGA
HOXD3 FWD	CACCTCCAATGTCTGCTGAA
HOXD3 REV	CAAAATTCAAGAAAACACACACA
INSL5 FWD	GAAGGTTTTGCGCTGGATT
INSL5 REV	GATCCCTCAAGCTCAGCAAG
MSX2 FWD	GGTCTTGTGTTTCCTCAGGG
MSX2 REV	AAATTCAGAAGATGGAGCGG
MUC2 FWD	TGTAGGCATCGCTCTTCTCA
MUC2 REV	GACACCATCTACCTCACCCG
ONECUT1 Fwd	TTTTTGGGTGTGTTGCCTCT
ONECUT1 Rev	AGACCTTCCGGAGGATGTG
PDX1 FWD	CGTCCGCTTGTTCTCCTC
PDX1 REV	CCTTTCCCATGGATGAAGTC
PPIA (CPHA) FWD	CCCACCGTGTTCTTCGACATT
PPIA (CPHA) REV	GGACCCGTATGCTTTAGGATGA
SATB2 FWD	CCACCTTCCCAGCTTGATT
SATB2 REV	TTAGCCAGCTGGTGGAGACT

[00133] Quantification of immunofluorescence images. Image quantitation of whole embryos was done by splitting images into separated channels and then measuring pixel area using ImageJ (NIH). Pixel area was determined for each channel, the ratio between channels was determined and the ratio for control treated embryos was represented as 100. Quantitation of in vitro and in vivo grown organoids was done on sections from which images were captured as explained above. The number of CDX2, GATA4 and SATB2 positive nuclei were quantified using the spot function in [marls following calibration with human biopsy samples.

[00134] RNA isolation and QPCR. RNA was extracted using Nucleospin® RNA extraction kit (Macharey-Nagel) and reverse transcribed into cDNA using Superscript VILO (Invitrogen) according to manufacturer's protocols. QPCR primers were designed using the qPrimerDepot webased tool (primerdepot.nci.nih.gov). Primer sequences are listed in Table 3. QPCR was performed using Quantitect SYBR® Green PCR kit (Qiagen) and a QuantStudio TM 6 Flex Real-Time PCR System (Applied Biosystems).

[00135] Table 3. Antibodies used. See FIGS 1-6.

ANTIBODY	HOST	Catalog number	Dilution
B-Catenin	rabbit	Santa Cruz #sc-7199	1:200
CDH17*	rabbit	Sigma #HPA023616	1:1,500
Cdx2	mouse	BioGenex cdx2-88	1:300
Cdx2	rabbit monoclonal	Cell Marque EPR2764Y	1:100
Chr-A (C20)	goat	Santa Cruz #sc-1488	1:100
DEFA5*	mouse monoclonal	Novus BiologicalsNB110-60002	1:60,000
E-Cadherin	goat	R&D #AF648	1:400
E-Cadherin (mouse-specific)	rat	R&D #MAB7481	1:500
E-Cadherin	mouse	R&D #AF648	1:500
FoxA2	goat	Santa Cruz #sc-6554	1:500

GATA4	goat	Santa Cruz #sc-1237	1:100
GATA4	rabbit	Santa Cruz #sc-9053	1:100
GFP (green fluorescent protein)	rabbit	Invitrogen #A11122	1:1,000
Ghrelin	goat	Santa Cruz #sc-10368	1:500
GIP (Gastric Inhibitory Polypeptide)	goat	Santa Cruz #sc-23554	1:500
GLP-1	mouse	BioVision #3104-100	1:200
HNF-6 (ONECUT1)	rabbit	Santa Cruz #sc-13050	1:100
INSL5 (H-110)*	rabbit	Santa Curz #sc-67190	1:100
KI67	rabbit monoclonal	Cell Marque SP6	1:100
Motilin	mouse monoclonal	Santa Cruz #sc-376605	1:100
Mucin 5B*	rabbit	Santa Cruz #sc-20119	1:100
Mucin2 (MUC2)	rabbit	Santa Cruz #sc-15334	1:200
Peptide YY	rabbit	Abcam #ab22663	1:1000
pSmad 1/5/8 (Discontinued and replaced with 13820S)	rabbit	Cell Signaling 9511S	1:100
pSmad 2/3	rabbit	Cell Signaling 9510S	1:100
SATB2	rabbit monoclonal	Cell Marque EP281	1:100
SATB2 (SATBA4610)*	mouse monoclonal	Santa Cruz #sc-81376	1:100
Sox9	rabbit	Millipore #AB5535	1:10,000
Alexafluor ® Donkey anti-goat 488	donkey	Life Technologies A-11055	1:500
Alexafluor ® Donkey anti-goat 568	donkey	Life Technologies A-11057	1:500
Alexafluor ® Donkey anti-mouse 568	donkey	Life Technologies A-10037	1:500
Alexafluor ® Donkey anti-rabbit 647	donkey	Life Technologies A-31573	1:500
Alexafluor ® Donkey anti-rat 488	donkey	Life Technologies A-21208	1:500

[00136] Identification of SATB2 as a large intestinal marker.

[00137] To identify markers of large intestine, Applicant first used GNCPro http://gncpro.sabiosciences.comigncpro/expression_grapherphp to identify transcription factors upregulated in colon (compared to other tissues) based on the University of Tokyo database. Based on this search, SATB2 was the 6th ranked gene in colon. To verify that SATB2 is indeed upregulated in the colon, Applicant searched SATB2 expression using the TiGER database (hftp://bioinfo.wilmer.ihu.edu/tiger/db gene/SATB2-index.html). To further confirm the expression of SATB2 in the colon, and to examine protein expression across numerous tissues, Applicant used the Human Protein Atlas (http://www.proteinatlas.org/search/satb2). A similar approach was used to identify other markers of large intestine/colon.

[00138] **Public RNA-seq accession numbers.** Adult small intestine and large intestine RNA-seq data were downloaded from the public database E-MTAB-1733. These data sets represent whole organ tissue which includes the epithelium and muscle layers. Accession numbers for the small intestine samples: ERR315344, ERR315381, ERR315409, ERR315442, ERR315461. Accession numbers for the large intestine samples: ERR315348, ERR315357, ERR315484. For FIG. 9B, processed FPKM data was downloaded from https://qithub.com/hilldr/Finkbeiner StemCellReports2015. These data include adult duodenum (ERS326992, ERS326976) and small intestine samples listed above from E-MTAB-1733 as well as human fetal intestinal (also whole organ) samples from GSE18927. Accession numbers for human fetal small intestine are GSM1059508, GSM1059521, GSM1059486, GSM1059507, GSM1059517, GSM1220519. For FIG. 9C, data was obtained from GEO accession GSE66749 platform GLP5175. The following samples were used: GSM1385160, GSM1385161, GSM1385162, GSM1385163, GSM1385164, GSM1385165, GSM1385166, GSM1385167, GSM1385168, GSM1385169, GSM1385170, GSM1385171, GSM1614646, GSM1614646. Sample values were determined using the GEO2R "profile graph" function and searching for GATA4 and SATB2 by their ID numbers (3086100 and 2594089 respectively).

[00139] RNA-seq sequence assembly abundance estimation. RNA library construction and RNA sequencing was performed by the Cincinnati Children's Hospital DNA Sequencing Core, using an Illumina HiSeq2500 platform. The quality of the Illumina sequencing run was evaluated by analyzing FASTQ data for each sample using FastQC version 0.10.1 http://www.bioinformatics.babraham.ac.uk/projects/fastqc to identify features of the data that may indicate quality problems (e.g. low-quality scores, over-represented sequences, inappropriate GC content, etc.). No major issues were identified by the QC analysis. Applicant used the software package Tuxedo Suite for alignment, differential expression analysis, and post-analysis diagnostics. Briefly, Applicant aligned reads to the reference transcriptome (UCSC hg19) using TopHat version 2.0.13 and Bowtie version 2.2.5 (Langmead et al., 2009). Applicant used default parameter settings for alignment, with the exception of: "—b2-very-sensitive" to maximize the accuracy of the read alignment, as well as "—no-coverage-search" and "—no-novel-juncs" limiting the read mapping to known transcripts. Cufflinks version 2.2.1 (Trapnell et al., 2012) was used for RNA abundance estimation. UCSC hgl9.fa was used as the reference genome sequence and UCSC hgl9.gtf was used for transcriptome annotation. Applicant applied the following parameters in Cufflinks: "—multi-read-correct" to adjust expression calculations for reads that map in more than one locus, and "—compatible-hits-norm" and "—upper-quartile —norm" for normalization of expression values. Normalized FPKM tables were generated using the CuffNorm function. RNA sequence assembly and transcriptional analysis was conducted using the 64-bit Debian Linux stable version 7.10 ("Wheezy") platform.

[00140] Differential expression analysis.

[00141] All plots and statistical analyses were conducted in R version 3.3.1 (2016-06-21). Plots were generated using the R package 'ggplot2' (Ginestet, 2011). Differential expression analysis and statistical tests of Cufflinks output were completed with the R package 'SeqRetriever' 'SeqRetriever' version 0.6 https://github.com/hilldr/SeqRetrieyer. Hypergeometric means testing was used to evaluate relative enrichment of shared gene expression signatures between groups using

the R package 'GeneOverlap' http://shenlab-sinai.cithub.io/shenlab-sinai/. The complete RNA-seq FASTQ processing pipeline and analysis scripts are available at https://qithub.com/hilldr/Munera2016.

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[00220] All percentages and ratios are calculated by weight unless otherwise indicated. All percentages and ratios are calculated based on the total composition unless otherwise indicated.

[00221] It should be understood that every maximum numerical limitation given throughout this specification includes every lower numerical limitation, as if such lower numerical limitations were expressly written herein. Every minimum numerical limitation given throughout this specification will include every higher numerical limitation, as if such higher numerical limitations were expressly written herein. Every numerical range given throughout this specification will include every narrower numerical range that falls within such broader numerical range, as if such narrower numerical ranges were all expressly written herein.

[00222] The dimensions and values disclosed herein are not to be understood as being strictly limited to the exact numerical values recited. Instead, unless otherwise specified, each such dimension is intended to mean both the recited value and a functionally equivalent range surrounding that value. For example, a dimension disclosed as “20 mm” is intended to mean “about 20 mm.”

[00223] Every document cited herein, including any cross referenced or related patent or application, is hereby incorporated herein by reference in its entirety unless expressly excluded or otherwise limited. The citation of any document is not an admission that it is prior art with respect to any invention disclosed or claimed herein or that it alone, or in any combination with any other reference or references, teaches, suggests or discloses any such invention. Further, to the extent that any meaning or definition of a term in this document conflicts with any meaning or definition of the same term in a document incorporated by reference, the meaning or definition assigned to that term in this document shall govern.

[00224] While particular embodiments of the present invention have been illustrated and described, it would be obvious to those skilled in the art that various other changes and modifications can be made without departing from the spirit and scope of the invention. It is therefore intended to cover in the appended claims all such changes and modifications that are within the scope of this invention.

CLAIMS

What is claimed is:

1. A method of inducing formation of a human colon organoid, comprising the steps of
    a. contacting definitive endoderm (DE) with an FGF signaling pathway activator and a WNT signaling pathway activator (for example, CHIRON/GSK2 inhibitor) for a period of time sufficient for said DE to form a mid-hindgut spheroid;
    b. contacting the mid-hindgut spheroid of step (a) with a BMP activator and an EGF signaling pathway activator for a period of time sufficient to form said human colon organoid, wherein said human colon organoid expresses SATB2.
2. The method of Claim 1 wherein said DE is derived from a precursor cell selected from an embryonic stem cell, an embryonic germ cell, an induced pluripotent stem cell, a mesoderm cell, a definitive endoderm cell, a posterior endoderm cell, a hindgut cell or combinations thereof.
3. The method of claim 1 or 2, wherein said FGF signaling pathway activator is selected from a small molecule FGF signaling pathway activator, a protein-based FGF signaling pathway activator, FGF1, FGF2, FGF3, FGF4, FGF10, FGF11, FGF12, FGF13, FGF14, FGF15, FGF16, FGF17, FGF18, FGF19, FGF20, FGF21, FGF22, FGF23, or combinations thereof.
4. The method of any preceding claim, wherein said WNT signaling pathway activator is selected from a protein Wnt signaling pathway activator, a small molecule Wnt signaling pathway activator, preferably Lithium Chloride; 2-amino-4,6-disubstituted pyrimidine (hetero) arylpyrimidines; IQ1; QS11; NSC668036; DCA beta-catenin; 2-amino-4-[3,4-(methylenedioxy)-benzyl-amino]-6-(3-methoxyphenyl) pyrimidine, Wnt1, Wnt2, Wnt2b, Wnt3, Wnt3a, Wnt4, Wnt5a, Wnt5b, Wnt6, Wnt7a, Wnt7b, Wnt8a, Wnt8b, Wnt9a, Wnt9b,

Wnt10a, Wnt10b, Wnt11, Wnt16, a GSK3 inhibitor, preferably CHIRON, or combinations thereof.

5. The method of any preceding claim, wherein said BMP activator is selected from BMP2, BMP4, BMP7, BMP9, a small molecule that activates the BMP pathway, a protein that activate the BMP pathway Noggin, Dorsomorphin, LDN189, DMH-1, ventromophins, and combinations thereof.
6. The method of any preceding claim, wherein said period of time sufficient for said DE to form a mid-hindgut spheroid is determined by expression of CDX2 by said mid-hindgut spheroid of step (a).
7. The method of any preceding claim, wherein said period of time sufficient for said mid-hindgut spheroid to form said human colon organoid by expression of SATB2 and CDX2 by a cell of said human colon organoid.
8. The method of any preceding claim, wherein said HCO is characterized by the presence of colonic enteroendocrine cells (EEC).
9. The method of any preceding claim, wherein said HCO is characterized by the presence of crypts and is substantially free of villi.
10. The method of any preceding claim, wherein said HCO comprises colon-specific goblet cells.
11. The method of any preceding claim, wherein said HCO is substantially free of Paneth cells.
12. The method of any preceding claim, wherein said HCO secretes colon-specific hormone INSL5.
13. An HCO obtained according to the method of any of claims 1 through 7.
14. A method of forming colonic tissue, comprising engrafting the HCO of any of claims 1 through 7 under a kidney capsule of a mammal, preferably a rodent, preferably an immunocompromised rodent, preferably an immunocompromised mouse.
15. A method of determining the efficacy and/or toxicity of a potential therapeutic agent for a disease selected from colitis, colon cancer, polyposis syndromes, and/or irritable bowel syndrome, comprising contacting said potential

therapeutic agent with the HCO of any of claims 1 through 12 for a period of time sufficient to determine the efficacy and/or toxicity of said potential therapeutic agent.

16. An immunocompromised rodent comprising the HCO of any preceding claim.
17. An intestinal colonoid derived from the HCO of any preceding claim.
18. The intestinal organoid of claim 17, wherein said intestinal organoid is free of one or more of an immune function, innervation, blood vessels, villi, and Paneth cells.