WRN conditioned media is sufficient for in vitro propagation of intestinal organoids from large farm and small companion animals

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ABSTRACT
Recent years have seen significant developments in the ability to continuously propagate organoids derived from intestinal crypts. These advancements have been applied to mouse and human samples providing models for gastrointestinal tissue development and disease. We adapt these methods for the propagation of intestinal organoids (enteroids) from various large farm and small companion (LF/SC) animals, including cat, dog, cow, horse, pig, sheep and chicken. We show that LF/SC enteroids propagate and expand in L-WRN conditioned media containing signaling factors Wnt3a, R-spondin-3, and Noggin (WRN). Multiple successful isolations were achieved for each species, and the growth of LF/SC enteroids was maintained to high passage number. LF/SC enteroids expressed crypt stem cell marker LGR5 and low levels of mesenchymal marker VIM. Labeling with EdU also showed distinct regions of cell proliferation within the enteroids marking crypt-like regions. The ability to grow and maintain LF/SC enteroid cell lines provides additional models for the study of gastrointestinal developmental biology as well as platforms for the study of host-pathogen interactions between intestinal cells and zoonotic enteric pathogens of medical importance.

KEY WORDS: Organoid, Enteroid, Crypt, Intestine, Farm animal, Companion animal, Conditioned media

INTRODUCTION
The development of primary cell lines for tissue culture has been an integral foundation to the study of cellular and molecular biology. The long term propagation of tissue culture cell lines works better for certain cell types than others. This is especially true for intestinal epithelial cells which have historically been resistant to expansion in culture, even with immortalization techniques such as SV40 transfection. This problem has largely been solved with the recent development of methods to isolate and expand intestinal crypt cells. Intestinal crypts contain LGR5+ stem cells which are the progenitors of the other cell types in the intestinal villus, such as Paneth, goblet and epithelial cells (Biswas et al., 2015; Sato and Clevers, 2013). Three factors, Wnt3a, R-spondin and Noggin (WRN), are required to keep LGR5+ cells growing in a stem-like state (Sato et al., 2009). When cultured in a 3D matrix with media containing the WRN factors, mouse intestinal crypt cells expand into organoid structures allowing for the continued propagation of intestinal cells. This has also been shown to be relevant for human intestinal cell lines (Jung et al., 2011; Sato et al., 2011a; VanDussen et al., 2015).

To facilitate the growth and maintenance of intestinal organoids, a mouse fibroblast cell line was engineered to secrete the three WRN factors cloned from murine transcripts, called the L-WRN cell line (Miyoshi et al., 2012; Miyoshi and Stappenbeck, 2013; Willert et al., 2003). Conditioned media (CM) cultured from these cells is effective in growing both mouse and human intestinal crypt organoids, demonstrating its usefulness across diverse organisms (Miyoshi and Stappenbeck, 2013; VanDussen et al., 2015). As intestinal crypt organoids from mouse and human samples currently serve as extensively studied models of development and disease (Clevers, 2016; Dedhia et al., 2016; Foulke-Abel et al., 2014; Jackson and Lu, 2016), we sought to expand the available intestinal organoid (enteroid) cell lines to include other species representing large farm and small companion (LF/SC) animals of veterinary relevance, which are also hosts for various zoonotic pathogens of importance to human health. Enteroids represent the relevant cell types for the growth of enteric pathogens, many of which develop into enteric stages within the terminal ileum of the small intestine, allowing for the possibility of culturing these infectious organisms in vitro. This strategy has recently shown great promise with the report of the growth of human noroviruses in human enteroids (Etayebi et al., 2016). LF/SC enteroids may provide similar platforms for intracellular enteric pathogens such as the growth of Toxoplasma gondii enteric stages within cat enteroids.

RESULTS AND DISCUSSION
WRN signaling molecules are conserved in LF/SC animals
Given the effectiveness of the WRN factors in stimulating the growth of both mouse and human intestinal enteroids, we were determined to test the activity of CM containing these factors on the growth of enteroids from animals of veterinary relevance. Protein alignments of human, mouse and LF/SC animal Wnt3a (Fig. 1A), R-spondin-3 and Noggin (Fig. S1) show broad protein sequence conservation for all three factors. We obtained the L-WRN cell line from the American Type Culture Collection (ATCC) to produce L-WRN cell conditioned media (50% L-WRN CM), and used it to grow intestinal enteroids (Fig. 1B) (Miyoshi and Stappenbeck, 2013). This media was first tested for the growth of mouse intestinal crypt derived enteroids, which rapidly expanded after isolation from the small intestine, eventually to high passage number (P>10) (Fig. 1C), confirming the effectiveness of the media. This growth was specific to 50% L-WRN CM as mouse enteroids failed to develop in DMEM +10% FBS (D10) after crypt isolation. Additionally, after being transferred to L cell conditioned media lacking WRN factors (50% L CM), high passage enteroids previously maintained in 50% L-WRN CM lost morphology breaking apart into individual cells and failing to expand with subsequent passage (Fig. 1C).
Intestinal crypt-derived enteroids from various LF/SC animals grow and expand to high passage

We began working relationships with local animal processing and shelter facilities to obtain tissue samples from the terminal ileum of the small intestine from a variety of LF/SC animals, including: Felis catus (cat), Canis familiaris (dog), Bos taurus (cow), Equus caballus (horse), Sus domesticus (pig), Ovis aries (sheep) and Gallus gallus (chicken – cecum) (Table 1). Multiple independent animals were sampled for each species. After isolation, crypts were cultured in either 50% L-WRN CM or media lacking the WRN protein.
factors (D10). The majority of crypt samples cultured in 50% L-WRN CM expanded and grew for several passages and lines could be maintained in 50% L-WRN CM to high passage number over long periods of time (Table 1), whereas none of the isolated crypts cultured in D10 grew to the first passage (Fig. 2A).

Small enteroids could be observed in 50% L-WRN CM within the first day after isolation and increased in number and size by the end of the first week (Fig. 2A). Enteroids from all LF/SC animals expanded and many began to obtain crypt-like folds with subsequent passages (Fig. 2A, P5 and P>10). High passage enteroid lines were maintained at high density (Fig. 2A, P>10, 500 µm). Like the mouse enteroids, LF/SC enteroids failed to grow after isolation in D10 media or after passage to 50% L CM when initially grown in 50% L-WRN CM to high passage (Fig. 2A), demonstrating the requirement for the WRN factors to stimulate enteroid growth as D10 and 50% L CM lack the WRN factors. Additionally, LF/SC enteroids can be cryopreserved, thawed, and expanded, providing a banked resource for continued experimentation (Fig. S2). The LF/SC enteroid passage history demonstrates the growth potential of these lines, where the cumulative fold expansion increased over time as enteroids were passed from well to well at high density (Fig. 2B). Likewise, the number of enteroids increased for high passage LF/SC lines when they were passed at a ratio of 1:2 over two passages (Fig. 2C).

Although we have been able to grow one cat intestinal enteroid line to relatively high passage (P18) (Table 1), and have demonstrated the requirement of 50% L-WRN CM for cat enteroid growth (Fig. 2A), cat enteroids cease to expand around P10 and begin to growth arrest around P13-P18 (Fig. 3). We are not certain why this limited expansion is restricted to the cat samples. Enteroids from all other LF/SC species tested here continue to grow and can be maintained at high density well past P10. We did observe a mesenchymal-like cell type growing with the cat enteroids (Fig. 2A, P5) which wane in number around P7-P9 before the enteroids begin to growth arrest, suggesting these cell types are needed for cat enteroid growth. Indeed, culture systems for intestinal cell growth (Fig. S2). The LF/SC enteroid passage history demonstrates the growth potential of these lines, where the cumulative fold expansion increased over time as enteroids were passed from well to well at high density (Fig. 2B). Likewise, the number of enteroids increased for high passage LF/SC lines when they were passed at a ratio of 1:2 over two passages (Fig. 2C).

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We show that culturing methods for growing intestinal crypt-derived mouse and human enteroids are applicable when applied to a number of animals of veterinary relevance. LF/SC enteroids grow and expand when cultured with 50% L-WRN CM, can be maintained to high passage number, and can be cryopreserved allowing for their use as resources for downstream experimentation. These cell lines offer additional models for the study of gastrointestinal development and disease that are pertinent to both veterinary and human medicine. In addition, these cell lines can be used to study host-pathogen interactions of zoonotic enteric pathogens and the intestinal cells with which they associate. Although we have not tested the individual requirements of Wnt3a, R-spondin-3 and Noggin in this study, this could be pursued in the future using cell lines that make conditioned media for each of these factors separately (Ettayebi et al., 2016; Heijmans et al., 2013). For example, in some platforms mouse small-intestinal enteroids can be cultured with media cocktails that contain just R-spondin and IGF-1 (Reynolds et al., 2014; Simmons et al., 2007), Prostaglandin E2 (PGE2) (Goessling et al., 2009; Jung et al., 2011; Pierzchalska et al., 2012), or mouse Wnt-2b and human Gremlin (Aoki et al., 2016; Szepourginski et al., 2017). None of these conditions rescued the cat enteroids to significantly improve growth beyond that in 50% L-WRN CM alone (Fig. 3). We continue to test other conditions in an attempt to grow the cat enteroids to higher passage number.

### LF/SC enteroids express LGR5 and contain proliferating crypt-like regions

The growth specificity of LF/SC enteroids in 50% L-WRN CM suggests the WRN factors are sufficient to sustain LGR5⁺ stem cells within the LF/SC enteroids, providing for their propagation, thus increasing enteroid size and cell number over time (Fig. 2). We harvested RNA from high passage LF/SC enteroids to determine the expression of stem cell marker LGR5 by qPCR, using whole intestinal tissue as a control that was collected and cryopreserved at the time of crypt harvest. The control tissue represents the various cell types of the intestine, containing tissues of the serosa, muscularis, submucosa, and mucosa. Enteroids from dog, cow, sheep and chicken all expressed LGR5 at or above the control tissue (Fig. 4A). Although lower than control tissue, LGR5 expression was also detected in the cat, horse and pig samples suggesting the presence of LGR5⁺ cells in these enteroids as well. LGR5 was low or not detected in non-stem cell control kidney epithelial cells from cat (CRFK) and cow (MDBK), respectively. We also determined the expression of mesenchymal marker vimentin (VIM) in the LF/SC enteroids (Fig. 4A). As expected, VIM expression in the two control kidney lines CRFK and MDBK was robust. In contrast to LGR5 expression, VIM expression was significantly lower than control tissue in the dog, cow, horse, pig, sheep and chicken enteroids. The low expression of VIM in these samples suggests they are able to grow in 50% L-WRN CM without the presence of mesenchymal cells (Sato et al., 2009; VanDussen et al., 2015). VIM was expressed above the control tissue in the cat enteroid line, further supporting the possibility that mesenchymal cells are present and required for the growth and expansion of cat enteroids.

LF/SC enteroids are a collection of continuously spaced cells (Fig. 4B, DAPI) with morphological characteristics similar to enteroids from mouse and human samples (Fig. 1C) (Date and Sato, 2015; Mahe et al., 2013; Sato et al., 2011a, 2009), containing budding structures producing invaginations and folds reminiscent of crypt-villous units (Fig. 4B). In addition, brief labeling with EdU revealed distinct regions of cell proliferation (Fig. 4B), many of which are in areas exhibiting crypt-like budding and folding.

### Table 1. Summary of isolation and maintenance of LF/SC organoids

<table>
<thead>
<tr>
<th>Species</th>
<th>Total harvested</th>
<th>Contam</th>
<th>Growth</th>
<th>High Pass Enteroid Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat</td>
<td>9</td>
<td>3</td>
<td>4</td>
<td>P18 67</td>
</tr>
<tr>
<td>Dog</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>P64 229</td>
</tr>
<tr>
<td>Cow</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>P45 165</td>
</tr>
<tr>
<td>Horse</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>P46 168</td>
</tr>
<tr>
<td>Pig</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>P49 174</td>
</tr>
<tr>
<td>Sheep</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>P66 239</td>
</tr>
<tr>
<td>Chicken</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>P35 125</td>
</tr>
</tbody>
</table>
Noggin because Paneth cells within enteroids secrete Wnt3 (Sato et al., 2011b, 2009). The L-WRN conditioned media used here is a relatively simple, inexpensive, robust and readily attainable culture platform compared to other alternatives. The successful culturing of LF/SC enteroids promises to increase the accessibility of these studies to laboratories not associated with facilities compatible with LF/SC animals. Furthermore, it will decrease the number of animals and the associated housing costs required to conduct gastrointestinal related research using LF/SC organisms.

**MATERIALS AND METHODS**

**Media and L-WRN cell line**

D10 media is DMEM high glucose (Thermo Fisher, Waltham, MA, USA, Cat# 12800) supplemented with 10% FBS (VWR Seradigm Premium Grade). The L (CRL-2648) and L-WRN (CRL-3276) cell lines were obtained from American Type Culture Collection (ATCC). The 50% L-WRN conditioned media (50% L-WRN CM) was made as previously described (Miyoshi and Stappenbeck, 2013) using the L-WRN cell line, which was derived from the L cell line (CRL-2648). The L cell conditioned media is media incubated with the L cell line (CRL-2648) which lacks the WRN factors, thus 50% L cell conditioned media (50% L CM).

**Animals**

All Louisiana State University (LSU) Institutional Animal Care and Use Committee (IACUC) protocols were followed for mouse tissue collection. All LSU IACUC guidelines were followed for intestinal tissue collection from LF/SC animal carcasses at local processing and shelter facilities, such as not handling live animals or in any way being involved in the euthanasia schedule.

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Fig. 2. 50% L-WRN CM is required for LF/SC enteroid growth and expansion. (A) Enteroids from LF/SC animals cultured with 50% L-WRN CM expand soon after crypt isolation (Day 1), growing to large size after passage (Day 6), and continue to expand and obtain crypt-like morphology at higher passage (white arrows) (P5 and P>10). Lower magnification shows enteroids were maintained at high density throughout passage history (P>10, 500 µm). Enteroids fail to grow when cultured in D10 after isolation (Day 6) or when passed to 50% L CM after high passage (P>10) growth in 50% L-WRN CM, no data (N/D). (B) Fold expansion of wells containing LF/SC enteroids. LF/SC enteroids grown in 24-well plates were maintained at high density. The ratio of per well expansion was recorded at each passage throughout the passage history. (C) Number of enteroids expands with each passage. A total of 200 high passage (P>10) enteroids were seeded to two wells and the number of enteroids was counted after 3-4 days of growth, and again after subsequent passage splitting 1:2, n=3. Cat samples are not included in B or C due to the lower passage and density of enteroids. Error bars indicate ±s.d.
Protein alignments

The human and mouse protein sequence of Wnt3a, R-spondin, and Noggin were used to find the LF/SC orthologs using NCBI Homologene (https://www.ncbi.nlm.nih.gov/homologene) and/or NCBI BLAST (https://blast.ncbi.nlm.nih.gov/Blast.cgi) against the appropriate genome. The following protein sequences were obtained from NCBI and used to make alignments in UGENE (Okonechnikov et al., 2012) using the Kalign algorithm (Edgar, 2004); Wnt3a: human (NP_149122.1), mouse (NP_035548.1), cat (XP_003980679.1), dog (XP_539327.3), cow (XP_015327344.1), horse (XP_014595070.1), pig (XP_003123669.1), goat (XP_013820431.1), sheep (XP_012026443.1), chicken (NP_001165072.1); R-spondin-3: human (NP_116173.2), mouse (NP_082627.3), cat (XP_003986583.1), dog (XP_005615677.2), cow (NP_001069502.1), horse (ABV31708.1), pig (XP_001926731.4), goat (XP_005684536.1), sheep (XP_004111851.1), chicken (XP_004940314.1); Noggin: human (NP_005441.1), mouse (NP_032737.1), cat (XP_011278221.1 and XP_011278233.1), dog (BAJ24018.1), cow (XP_002695600.1), horse (AAM4779.1), pig (NP_001137163.1), goat (XP_013827246.1), sheep (NP_001167581.1), chicken (AAC83550.1).

Cryopreserving of cell lines

To cryo-preserve the cell lines, Matrigel with enteroids was scrapped with a pipette tip, centrifuged (200 rcf), suspended in 20 µl of Matrigel per well, seeded to a 24-well plate and grown in 50% L-WRN CM with 10 µM Y-27632 and 10 µM SB-431542 in an attempt to rescue the cat enteroids include: A83-01 (10 µM; BioVision, Cat # 1725-1), SB202190 (10 µM; AdipoGen, San Diego, CA, USA, Cat # AGCR10028M001), human FGF-4 (500 ng/ml; Peprotech, Rocky Hill, NJ, USA, Cat # 100-31), human FGF-2 (FGF-basic) (100 ng/ml; Peprotech, Cat # 100-18B), human FGF-10 (100 ng/ml; Peprotech, Cat # 100-26), nicotinamide (100 µM; Alfa Aesar, Tewksbury, MA, USA, Cat # A15970-22), human IGF-I (100 ng/ml; Peprotech, Cat # 100-11), PGE2 (5 µg/ml; TCI America, Portland, OR, USA, Cat # P1884-1MG), mouse Wnt-2b (20 ng/ml; R&D Systems, Minneapolis, MN, USA, Cat # 3900-WN/CF), chicken Gremlin (200 ng/ml; Peprotech, Cat # 120-42).

Protein alignments

Protein sequences were aligned in UGENE (Okonechnikov et al., 2012). Details and accession numbers are provided in the Supplementary Materials.

Microscopy

Brightfield images of enteroid in Matrigel were taken with an Olympus IX71 microscope, Olympus U-CMAD3 camera (10×) or a Leica DMIRB microscope, Olympus DP80 camera (2.5×) using the cellSens software (Olympus).
Enteroid counts
Fold expansion of enteroids over time was determined by recording the ratio at which wells were split at each passage throughout the passage history of that cell line, for example, two wells of enteroids passed to four new wells (1:2).

To determine enteroid expansion during passage, 200 high passage (P10) enteroids were seeded in Matrigel matrix to two wells (P1). After 3-4 days of growth the enteroids were counted and passed (P2), split 1:2. Again, after 3-4 days of growth the enteroids were counted.

RNA isolation and qPCR
RNA from enteroids, control tissue, and kidney epithelial cells (CRFK and MDBK) was isolated using the RNeasy Plus mini kit (Qiagen) according to the manufacturer’s protocol, with DNase treatment (Qiagen) on the tissue controls samples. The High Capacity RNA-to-cDNA kit (Thermo Fisher 4387406) was used to obtain cDNA from 500 ng of RNA. qPCR negative controls omitted the RT enzyme. qPCR was performed with the PowerUp™ SYBR™ Green Master Mix (Thermo Fisher A25742) with a final primer concentration of 0.5 µM (Table S1) and 10 ng of cDNA, and run on an Applied Biosystems (ABI) 7900HT Sequence Detection System. Data are the average of three independent cDNA samples and technical replicates conducted for each sample per qPCR run. Data were normalized to GAPDH values, control tissue values were set to 1 and enteroid values expressed as a ratio to control tissue using the 2-ΔΔCt method (Livak and Schmittgen, 2001). Raw data for three independent cDNA samples and their technical replicates were analyzed in ExpressionSuite Software v 1.0.3 (Thermo Fisher). Biological groups were designated by sample type, with control tissue selected as the biological reference group, and data were normalized using GAPDH as an endogenous control. One standard deviation was used to determine the RQ minimum and maximum (error bars).

Immunofluorescence assays
Enteroids were suspended in 25 µl of 50% Matrigel diluted in PBS, plated as a thin mound in an 8-well chamber slide (Corning), and cultured in 200 µl 50% L-WRN CM at 37°C for two days. Cultures were rinsed with PBS prior to fixation and between incubations steps. Click-IT EdU Alexa Fluor 647 assay (Thermo Fisher) was used to label proliferating cells within the enteroids according to the manufactures protocol and O’Rourke et al. (2016). Raw data for three independent cDNA samples and their technical replicates were analyzed in ExpressionSuite Software v 1.0.3 (Thermo Fisher). Biological groups were designated by sample type, with control tissue selected as the biological reference group, and data were normalized using GAPDH as an endogenous control. One standard deviation was used to determine the RQ minimum and maximum (error bars).
Aldrich, Cat # SAB4200473) in 1% BSA at 4°C O/N, then 1:250 secondary goat α-mouse Alexa Fluor 488 (Thermo Fisher) in 1% BSA at 4°C for 3 h, nuclei were stained with DAPI (1 μg/ml) for 10 min, and slides were mounted with ProLong Diamond (Thermo Fisher). Images were taken on a Zeiss Observer.Z1 Axio microscope with z-stack layering and processed with the ‘best fit’ option to reduce background, slight gamma value adjustment, then deconvolution and extended depth of focus. The negative control images were captured and processed the same as the comparable IFA.

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Competing interests

The authors declare no competing or financial interests.

Author contributions

Conceptualization: R.H.P.; Methodology: R.H.P., M.S.B.; Validation: R.H.P.; Formal analysis: R.H.P.; Investigation: R.H.P.; Resources: R.H.P., M.S.B.; Writing - original draft: R.H.P., M.S.B.; Writing - review & editing: R.H.P., M.S.B.; Visualization: R.H.P., M.S.B.; Supervision: M.S.B.; Project administration: M.S.B.; Funding acquisition: M.S.B.

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Supplementary information

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References


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