RESEARCH

INSL5 activates multiple signalling pathways and regulates GLP-1 secretion in NCI-H716 cells

Sheng Y Ang1, Bronwyn A Evans1, Daniel P Poole1, Romke Bron1, Jesse J DiCello1, Ross A D Bathgate2,3, Martina Kocan2, Dana S Hutchinson1,4 and Roger J Summers1

1Drug Discovery Biology, Monash Institute of Pharmaceutical Sciences, Monash University, Parkville, Victoria, Australia
2The Florey Institute of Neuroscience and Mental Health, University of Melbourne, Parkville, Victoria, Australia
3Department of Biochemistry and Molecular Biology, University of Melbourne, Melbourne, Victoria, Australia
4Department of Pharmacology, Monash University, Clayton, Victoria, Australia

Correspondence should be addressed to S Y Ang: sheng.ang@monash.edu

Abstract

Insulin-like peptide 5 (INSL5) is a newly discovered gut hormone expressed in colonic enteroendocrine L-cells but little is known about its biological function. Here, we show using RT-qPCR and in situ hybridisation that Insl5 mRNA is highly expressed in the mouse colonic mucosa, colocalised with proglucagon immunoreactivity. In comparison, mRNA for RXFP4 (the cognate receptor for INSL5) is expressed in various mouse tissues, including the intestinal tract. We show that the human enteroendocrine L-cell model NCI-H716 cell line, and goblet-like colorectal cell lines SW1463 and LS513 endogenously express RXFP4. Stimulation of NCI-H716 cells with INSL5 produced phosphorylation of ERK1/2 (Thr202/Tyr204), AKT (Thr308 and Ser473) and S6RP (Ser235/236) and inhibited cAMP production but did not stimulate Ca2+ release. Acute INSL5 treatment had no effect on GLP-1 secretion mediated by carbachol or insulin, but modestly inhibited forskolin-stimulated GLP-1 secretion in NCI-H716 cells. However, chronic INSL5 pre-treatment (18 h) increased basal GLP-1 secretion and prevented the inhibitory effect of acute INSL5 administration. LS513 cells were found to be unresponsive to INSL5 despite expressing RXFP4. Another enteroendocrine L-cell model, mouse GLUTag cells did not express detectable levels of Rxfp4 and were unresponsive to INSL5. This study provides novel insights into possible autocrine/paracrine roles of INSL5 in the intestinal tract.

Key Words
- INSL5
- RXFP4
- NCI-H716
- cell signalling
- GLP-1

Introduction

Insulin-like peptide 5 (INSL5) is a novel gastrointestinal (GI) hormone identified in colonic enteroendocrine L-cells along with glucagon-like peptide 1 (GLP-1) and peptide YY (PYY) (Grosse et al. 2014). The cognate receptor for INSL5 is the relaxin family peptide receptor 4 (RXFP4), a G protein-coupled receptor (GPCR) that couples to inhibitory Ga(i/o) proteins (Liu et al. 2003, 2005) and activates a number of signalling pathways including phosphorylation of extracellular signal-regulated protein kinases 1 and 2 (ERK1/2), p38 mitogen-activated protein kinases (p38MAPK), protein kinase B (AKT) and S6 ribosomal protein (S6RP) (Ang et al. 2017). INSL5 activates RXFP4 but not the other relaxin family peptide receptors, RXFP1-3 (Halls et al. 2015). Previous transcriptomic and in situ hybridisation studies indicated that, like INSL5, RXFP4 is predominantly expressed in the GI tract i.e. colon and rectum (Yue et al. 2014, Uhlén et al. 2015), and is localised in regions that resemble the colonic...
submucosal and myenteric plexuses (Grosse et al. 2014). Furthermore, RXFP4 immunoreactivity has been reported in normal human mucosa and human neuroendocrine tumours (NETs) (Mashima et al. 2013, Thanasupawat et al. 2013) arising from enteroendocrine cells (Gunawardene et al. 2011).

The physiological role of INSL5 is still unclear, but it was reported to be an orexigenic peptide upregulated during periods of energy deprivation and suggested to act via the enteric nervous system (Grosse et al. 2014). Most notably, exogenous administration of INSL5 stimulated feeding in wild type but not in Rxfp4-deficient mice. In addition, INSL5 appears to play a role in glucose metabolism with suggested actions on pancreatic β-cell insulin secretion (Burnicka-Turek et al. 2012, Luo et al. 2015) and hepatic glucose production (Lee et al. 2016). Furthermore, INSL5 reportedly stimulates ERK1/2 phosphorylation and promotes GLP-1 secretion in murine L-cell model GLUTag cell line (Luo et al. 2015), and RXFP4 is expressed in a number of mucin 2 (MUC2)-expressing, goblet-like human colorectal carcinoma cell lines (Mouradov et al. 2014). These findings suggest that INSL5 secreted from colonic L-cells is likely to act in an autocrine/paracrine manner on locally expressed RXFP4 to regulate gut functions such as peptide secretion from enteroendocrine cells and/or mucin secretion from goblet cells.

This study aims to elucidate the expression patterns of Insl5 and Rxfp4 in various mouse tissues and investigate whether INSL5 can stimulate signalling in enteroendocrine L-cells and/or goblet cells using various cell culture models, which would provide evidence for an autocrine/paracrine action of this gut hormone. We confirm that Insl5 is a product of L-cells in the colon while Rxfp4 expression was detected at low levels in various tissues, including the intestinal tract. In addition, we report that the human enteroendocrine L-cell model NCI-H716 cell line, and goblet-like colorectal cell lines LS513 and SW1463, endogenously express RXFP4. Importantly, in NCI-H716 cells, INSL5 stimulates signalling and regulates GLP-1 secretion, suggesting a potential novel biological role for INSL5 in mediating L-cell function.

Materials and methods

Mouse and tissue preparation

129SvEv wild-type (WT) and RXFP4-deficient (Rxfp4−/−) mice were obtained from Dr Johannes Grosse (Takeda Cambridge Limited, Cambridge, UK) (Grosse et al. 2014). WT and Rxfp4−/− mice were genotyped before use (Transnetx, Cordova, TN, USA). C57BL/6J mice were obtained from the Monash Animal Research Platform. All mice were bred and maintained at the Monash University (Parkville) animal housing facility. Tissues for RT-qPCR and in situ hybridisation experiments were from C57BL/6J and 129SvEv mice, respectively. The protocol used was approved by the Monash University Animal Ethics Committee (MIPS.2015.14) and conforms to the Australian Code for the Care and Use of Animals for Scientific Purposes. Male or female mice (12–16-week-old) were killed by CO2 inhalation and cervical dislocation, and tissues of interest dissected and frozen for RNA extractions or ileum and colon dissected and fat removed, fixed overnight in 4% (w/v) paraformaldehyde and cryoprotected with 30% (w/v) sucrose in diethyl pyrocarbonate-treated phosphate buffered saline (DEPC-PBS) for tissue staining. Fixed tissues were frozen in cryomoulds in Tissue-Tek (OCT, VWR International, QLD, Australia) and stored at −80°C until sectioning.

Cell culture

Human NCI-H716, LS513 and SW1463 cells were purchased from American Type Culture Collection (Manassas, VA, USA). GLUTag cells (Brubaker et al. 1998) were a kind gift from Professor Fiona M. Gribble (University of Cambridge, UK) with permission from Prof. Daniel J Drucker (University of Toronto, Canada). NCI-H716 cells were grown in suspension and maintained in complete media consisting of RPMI-1640 (Thermo Fisher Scientific) with 5% foetal bovine serum (FBS). GLUTag cells were grown in high glucose DMEM (Thermo Fisher Scientific) with 10% (v/v) FBS, and LS513 and SW1463 cells in high glucose DMEM with 5% (v/v) FBS. Cells were incubated at 37°C in a humidified chamber containing 5% CO2. Cells were seeded onto multi-well plates and grown in complete media for 48h before experimentation. NCI-H716 cells were plated onto multi-well plates coated with Cultrex basement matrix extract (Trevigen, Gaithersburg, MD, USA) at 100µg/mL to allow cell adhesion.

RNA isolation and cDNA synthesis

Total RNA was isolated from mouse tissues, and cell lines using RNeasy mini RNA purification kit (Qiagen) and DNase-treated using the Ambion DNA-free DNase kit (Thermo Fisher Scientific) according to the manufacturer’s instructions. cDNA was synthesised from 500ng RNA in a 10µL reverse transcriptase reaction using iScript Reverse Transcription Supermix kit for RT-qPCR (Bio-Rad).
qPCR
Quantitative polymerase chain reaction (qPCR) was performed as described previously (Ang et al. 2017) using a Mastercycler ep Realplex machine (Eppendorf, Hamburg, Germany) with the following TaqMan primers and probes (Thermo Fisher Scientific): Mouse – Insll5: Mm04210319_m1, Rxfp4: Mm00731536_s1, Ggcg: Mm00801714_m1, Gp1r: Mm00445292, Actb: Mm02619580_g1; Human – Insll5: Hs00193884_m1, RXFP4: Hs00704281_s1, GCG: Hs01031536_m1, GLP1R: Hs00157705_m1, ACTB: Hs01060665_g1. After denaturation at 95°C for 10 min, fluorescence was measured over 40 cycles (95°C for 15 s, 60°C for 2 min).

Generation of in situ hybridisation probes
Digoxigenin (DIG)-labelled Insll5 and Rxfp4 in situ hybridisation probes were generated by in vitro transcription (Supplementary methods, see section on Supplementary data given at the end of this article).

Combined in situ hybridisation and immunofluorescence
For detailed protocol, see Supplementary methods. Briefly, 12 μm sections of mouse colon and ileum were cut using a Leica CM3050 cryostat and mounted on Superfrost Plus slides (Thermo Fisher Scientific) and allowed to air-dry for an hour. Sections were hybridised with DIG-labelled Insll5 or Rxfp4 probe (1:100 each) overnight at 60°C, washed and incubated with horseradish peroxidase-(POD, 1:500, Roche) conjugated anti-DIG antibody before tyramide signal amplification with FITC-tyramide. Following in situ hybridisation, sections were blocked (2% BSA, 0.1% (v/v) Tween-20 in PBS), incubated with rabbit anti-proglucagon antibody (1:500, Abcam) overnight, washed with TBST and incubated with anti-rabbit Alexa594 secondary antibody (1:100, Thermo Fisher Scientific). Fluorescent wide-field images were acquired by tile-scanning using a Nikon Ti-E fluorescence microscope with a 20× objective and photo-stitched during acquisition in NIS-Elements software (Nikon Instruments).

Alphascreen protein phosphorylation
Phosphorylation of ERK1/2 (Thr202/Tyr204), AKT (Thr308 and Ser473) and S6RP (Ser235/236) was measured using Alphascreen SureFire kits (Perkin Elmer). GLUTag and LS513 cells were seeded onto 96-well plates and NCI-H716 cells were prepared in 24-well matrix-coated plates. On the day of experiment, cells were serum-starved for 4–6 h in low glucose (1 g/L) DMEM to reduce basal phosphorylation levels, and then stimulated with human INSL5 (100 nM) for up to 60 min in time course studies or with increasing concentrations of peptides (10–10–6.5 M) in concentration-response studies at 5 min (p-ERK1/2), 15 min (p-AKT) and 30 min (p-S6RP). At the end of INSL5 stimulation, cells were lysed and protein phosphorylation was measured as described previously (Ang et al. 2017).

Immunoblotting
All primary and secondary antibodies were from Cell Signalling Technology. NCI-H716 cells were grown in a 12-well plate and stimulated with INSL5 (100 nM) for up to 60 min and lysed with 80 μL of SDS sample buffer (62.5 mM Tris–HCl (pH 6.8), 4% SDS, 20% glycerol, 0.001% bromophenol blue and 5% β-mercaptoethanol). Cell lysates were transferred to microcentrifuge tubes, sonicated for 10–15 s to reduce viscosity and boiled at 95°C for 5 min to denature proteins. Protein samples were loaded onto 10% polyacrylamide gels and separated at 100 V for 2 h and electrotransferred to a polyvinyl difluoride membrane (0.45 μm, Bio-Rad). Membranes were blocked for 2 h with 5% BSA in TBST and incubated overnight at 4°C with phospho-ERK1/2 (1:1000; #9101) or phospho-AKT Ser473 (1:1000; #9271) rabbit primary antibodies. The following day, membranes were washed 5 times with TBST, incubated with HRP-conjugated anti-rabbit secondary antibody (1:2000; #7074), washed 5 times with TBST, re-probed with rabbit primary antibodies against total ERK1/2 (1:1000; #9102) or total AKT (1:1000; #9272) and immunoblots detected as before using the ECL detection method.

Inhibition of cAMP accumulation
Inhibition of forskolin-stimulated cAMP accumulation in NCI-H716 cells was measured using a LANCE cAMP kit (Perkin Elmer). Cells were seeded in 96-well plates and on the day of experiment, incubated in HBSS (Thermo Fisher Scientific) supplemented with 0.5 mM IBMX, 5 mM HEPES and 0.1% BSA. INSL5 (10−11–10−6.5) M was added
for 15 min followed by stimulation with forskolin (3 μM) for 30 min. Cells were lysed in ice-cold absolute ethanol and air-dried. Pellets containing cAMP were solubilised in 0.3% (v/v) Tween-20, 5 mM HEPES and 0.1% (w/v) BSA, and cAMP in the solute was measured according to the manufacturer’s protocol.

**Intracellular Ca\(^{2+}\) mobilisation**

NCI-H716 cells were prepared in a 96-well plate, loaded with the Ca\(^{2+}\) indicator Fluo-4 AM and real-time intracellular Ca\(^{2+}\) mobilisation during INSL5 stimulation measured on a FlexStation (Molecular Devices, Sunnyvale, CA, USA) as previously described (Ang et al. 2017).

**GLP-1 secretion**

NCI-H716 cells were grown overnight in complete RPMI media in 96-well plates and serum-starved with vehicle (0.02% DMSO) or INSL5 (100 nM) 18h prior to experimentation. On the day of experiment, cells were washed with PBS and incubated in secretion buffer (115 mM NaCl, 5 mM KCl, 24 mM NaHCO\(_3\), 1 mM MgCl\(_2\), 2.5 mM CaCl\(_2\), 25 mM HEPES, 5 mM glucose) and vehicle (0.02% DMSO) or INSL5 (100 nM) added for 15 min, followed by vehicle (0.04% DMSO) or secretagogues (100 μM carbachol, 100 nM insulin or 3 μM forskolin) for 90 min (Supplementary Fig. 1). 50 μM DPP4 inhibitor (DPP4-010, EMD Millipore) was included in the secretion buffer to prevent GLP-1 degradation. Media was collected and GLP-1 content was measured using an active GLP-1 HTRF kit (Cisbio, Codolet, France) according to the manufacturer’s protocol.

**Data and statistical analysis**

For RT-qPCR, data were expressed as the relative abundance of the gene of interest relative to the reference gene, β-actin (ACTB), using the following equation:

\[
2^{ΔCt}*1000
\]

where \(ΔCt= Ct_{\text{gene of interest}} - Ct_{\text{ACTB}}\)

For Alphascreen protein phosphorylation assays, data were expressed as a % of untreated (basal) response in the time course study or % vehicle response in the concentration-response study, for inhibition of cAMP accumulation as % forskolin (3 μM) response, for calcium mobilisation as % basal fluorescence intensity prior to ligand addition, and for GLP-1 secretion assay as picomolar concentration (pM). All graphs were plotted using Prism (v7.0) (GraphPad Software) and concentration-response curves fitted using a three-parameter Hill equation within Prism. INSL5 protein phosphorylation in the Alphascreen time course study was statistically compared to the untreated (basal) response using two-way ANOVA followed by Sidak’s multiple comparisons, while the GLP-1 response stimulated by various ligands was statistically compared to the untreated (basal) response using one-way ANOVA followed by Sidak’s multiple comparisons test.

**Peptides and drugs**

Lyophilized human INSL5 was purchased from Phoenix Pharmaceuticals (Burlingame, CA, USA) and reconstituted. Human insulin (I9278), carbachol (C4382) and forskolin (F6886) were from Sigma-Aldrich.

**Results**

**Expression patterns of Insl5 and Rxfp4 in mouse tissues**

Since metabolic phenotypes have been reported in mice with genetic ablation of Insl5 (Burnicka-Turek et al. 2012) or Rxfp4 (Grosse et al. 2014), we investigated mRNA expression patterns of Insl5 and Rxfp4 by RT-qPCR in the following metabolically relevant mouse tissues: skeletal muscle (hind limb), heart, pancreas, brown adipose tissue (BAT), inguinal adipose tissue (iWAT), epididymal adipose tissue (eWAT), ileum, colon and rectum. Insl5 expression was the highest in colonic mucosa followed by submucosa but was undetectable in external muscle (Fig. 1). Insl5 expression was undetectable in other regions that include ileum, skeletal muscle, heart, pancreas, BAT, iWAT and eWAT. By contrast, the proglucagon mRNA Gcg was highly expressed, as expected, in pancreas where glucagon is synthesised, and also found in ileum, colon and rectum, all regions where GLP-1 is produced (Fig. 1). Using combined in situ hybridisation and immunohistochemistry, Insl5 mRNA was localised in mouse colon to discrete cells that were also immunopositive for the GLP-1 precursor proglucagon (Fig. 2), in agreement with previous studies (Grosse et al. 2014, Lee et al. 2016). In line with our RT-qPCR data, no Insl5 mRNA was detected by in situ hybridisation in mouse ileum, whereas proglucagon immunoreactivity was still observed (Supplementary Fig. 2).

While Insl5 expression was confined to the mouse colorectum, its receptor Rxfp4 had a more general tissue expression pattern with transcripts detected at relatively low levels across all the tissues investigated. Rxfp4
expression was the highest in pancreas and was also detected in heart, skeletal muscle, rectum and all layers of ileum and colon (Fig. 3). In comparison, Glp1r was expressed abundantly in the pancreas, in line with known expression in insulin-producing β-cells (MacDonald et al. 2002). Consistent with the relatively poor tissue expression in mouse, we found the Rxfp4 in situ hybridisation signal weak and extremely difficult to detect in the colon. There was a faint perinuclear Rxfp4 signal that colocalised with proglucagon immunoreactivity in mouse colonic mucosa (Fig. 4), suggesting that Rxfp4 may be discretely expressed in a subset of colonic cells such as enteroendocrine L-cells. Unlike previously reports, we were not able to detect RXFP4 signals in enteric neurons using the in situ hybridisation approach.

**RXFP4 is expressed in human L-cell model NCI-H716 cell line and goblet-like colorectal cell lines LS513 and SW1463, but not in murine L-cell model GLUTag cell line**

Our RT-qPCR data, together with transcriptomic data published by others (Yue et al. 2014, Uhlén et al. 2015), indicate that RXFP4 is expressed in the GI tract. Thus, we focused our attention on cell lines with GI origin to investigate whether they express RXFP4 and could signal in response to INSL5. Moreover, INSL5 was recently shown to promote phosphorylation of ERK1/2 and to stimulate GLP-1 secretion in GLUTag cells (Luo et al. 2015). GLUTag cells are a murine model of enteroendocrine L-cells originally derived from a colonic tumour developed from transgenic mice expressing SV40 large T antigen under the control of the proglucagon promoter (Drucker et al. 1994, Gil-Lozano & Brubaker 2015) and are widely used to study GLP-1 release in response to a variety of L-cell stimuli (Lan et al. 2012, Parker et al. 2012, Gagnon et al. 2015, Luo et al. 2015). Here, using RT-qPCR, Rxfp4 mRNA was surprisingly undetectable in GLUTag cells. In contrast, Ins15 and Gcg were readily detected, with Gcg expressed at a higher level than Ins15 (Fig. 5A). This supports a previous microarray gene expression study of GLUTag cells that also found no Rxfp4 expression (Trabelsi et al. 2015). In contrast, NCI-H716 cells, a commonly used human model of enteroendocrine L-cells (Reimer et al. 2001, Jang et al. 2007, Lauffer et al. 2009, Lim et al. 2009) originally derived from ascites fluid of a patient with caecal adenocarcinoma (Park et al. 1987, Gagnon & Brubaker 2015), expressed reasonably high levels of
RXFP4. NCI-H716 also expressed GCG abundantly but INSL5 poorly (Fig. 5B). Two goblet-like cell lines, LS513 and SW1463, both derived from patients with Duke’s type C mucin-secreting caecal tumour (Leibovitz et al. 1976, Suardet et al. 1992), also expressed reasonably high levels of RXFP4, whereas INSL5 expression was undetectable in LS513 and poor in SW1463 (Fig. 5 C and D). LS513 cells have been used as models to demonstrate protective roles of mucins in epithelial cells (Gustafsson et al. 2013, Sheng et al. 2013, 2017), whereas SW1463 cells are regularly used as a cell model for colorectal cancer (Singh et al. 2012, Pinto et al. 2016, Emons et al. 2017).

**INSL5 stimulates phosphorylation of ERK1/2, AKT and S6RP and inhibits cAMP production in NCI-H716 cells**

Since NCI-H716 and LS513 endogenously expressed RXFP4, we performed pharmacological studies on these cells using the cognate ligand for human RXFP4, human INSL5. In a recombinant cell system stably expressing human RXFP4, INSL5 promoted phosphorylation of ERK1/2, AKT and S6RP and inhibited cAMP production (Ang et al. 2017). ERK1/2 and AKT pathways are widely implicated in cellular proliferation, differentiation, growth and survival (Manning & Cantley 2007, Turjanski et al. 2007), while S6RP is involved in protein synthesis (Ruvinsky & Meyuhas 2006). In time course experiments, exposure of NCI-H716 cells to INSL5 (100 nM) for up to 60 min produced phosphorylation of ERK1/2 (Thr202/Tyr204), AKT (Thr308 and Ser473) and S6RP Ser235/236. Maximum ERK1/2 phosphorylation occurred at 5 min, AKT (Thr308 and Ser473) phosphorylation at 15 min and S6RP phosphorylation at 30 min (Fig. 6A, B, C and D). INSL5 concentration-response relationships in NCI-H716 cells were constructed at time points corresponding to maximum protein phosphorylation. INSL5 (0.1–300 nM) caused concentration-dependent phosphorylation of ERK1/2 (Fig. 6E), AKT (Thr308 and Ser473; Fig. 6F and G) and S6RP (Fig. 6H) with pEC50 values ranging from 7.9 to 8.4. In addition, immunoblots for ERK1/2 and AKT (Ser473) performed in NCI-H716 cells following INSL5 stimulation (100 nM), showed similar phosphorylation patterns (Fig. 6I and J) to those observed in the Alphascreen time course assays. Exposure of NCI-H716 cells to human INSL5 (0.1–300 nM) also produced concentration-dependent inhibition of cAMP accumulation in response to forskolin (3 μM) (pEC50=8.0±0.3; Fig. 6K) reflecting activation of Gαi/o-coupled RXFP4. Since Ca2+ mobilisation is an important mechanism leading to GLP-1 secretion (for review see Reimann et al. 2012), the effect of INSL5 on
intracellular Ca\textsuperscript{2+} mobilisation was also investigated. INSL5 treatment up to 100 nM failed to stimulate a detectable Ca\textsuperscript{2+} response, whereas the muscarinic acetylcholine receptor agonist carbachol (10\textsuperscript{-4} M) caused a robust Ca\textsuperscript{2+} response (Fig. 6L).

Intriguingly, we were unable to observe INSL5 signalling in LS513 cells (Supplementary Fig. 3A, B, C, D and E), even though RXFP4 was clearly expressed in these cells (Fig. 5C). In addition, we were unable to adequately perform further pharmacological studies in SW1463 due to the poor growth of this cell line. Consistent with a lack of Rxfp4 expression in GLUTag cells, treatment with mouse INSL5 (100 nM) over 60 min, failed to produce phosphorylation of AKT (Thr\textsuperscript{308} or Ser\textsuperscript{473}) or S6RP Ser\textsuperscript{235/236} (Supplementary Fig. 4) both signalling events associated with RXFP4 activation (Ang et al. 2017). In contrast,
insulin (100nM) stimulated a robust AKT and S6RP response in the same cells.

**Effects of acute and chronic administration of INSL5 on GLP-1 secretion from NCI-H716 cells**

NCI-H716 is a model of human enteroendocrine L-cells, and as such we investigated the effects of INSL5 on GLP-1 secretion (Fig. 7). In cells exposed to chronic (18 h) vehicle, acute INSL5 treatment (100nM) had no significant effect on basal, carbachol or insulin-stimulated GLP-1 secretion ($P < 0.01$). However, in cells exposed to chronic (18 h) INLS5, acute INSL5 treatment had no effect on basal secretion and failed to inhibit forskolin-stimulated GLP-1 secretion, likely due to RXFP4 desensitisation by chronic INSL5 pre-treatment (Ang et al. 2017) or possibly downregulation of signalling effectors. Interestingly, cells chronically pre-treated with INSL5 displayed an increase in basal GLP-1 secretion ($P < 0.001$). This was not due to increased synthesis of GLP-1 precursor peptide proglucagon, since proglucagon peptide content remained unchanged in these cells (Supplementary Fig. 5A) or by an increased number of cells (Supplementary Fig. 5B).

**Discussion**

In this study, we demonstrate that Ins5 mRNA is expressed mainly in the mouse colonic mucosa in discrete cells that are also immunopositive for the GLP-1 precursor proglucagon, confirming Ins5 expression in enteroeendocrine L-cells (Grosse et al. 2014, Lee et al. 2016). Indeed, a similar co-expression pattern was observed in the human colon (Grosse et al. 2014) suggesting that INSL5 likely has important biological functions across different species. By comparison, we found RXfp4 expression in mouse tissues to be weaker, less region specific and more difficult to detect than Ins5. We were unable to detect RXfp4 in enteric neurons by in situ hybridisation, unlike previous reports (Grosse et al. 2014). The disparity may reflect the different hybridisation strategies employed, and different sensitivities between fluorescent (present study) and chromogenic detection methods. Other approaches such as RNAscope, RXfp4 Cre reporter mouse line or receptor autoradiography would be useful to clarify the expression and localisation of RXFP4 in native tissues.

Although expression of RXfp4 is detectable in mouse pancreas, the level is only 4% of that seen in NCI-H716 cells and less than 0.3% of that seen for Gp1r in pancreas. These data are consistent with a number of RNA sequencing studies on both mouse and human pancreatic islets. In 4–6 independent preparations of mouse freshly isolated primary α, β and δ cells, RXfp4 has FPKM values ranging from 0.0 to 0.26 (average 0.04) (Adriaenssens et al. 2016). These values are negligible compared to those for GPCRs known to be important in islet function, for example, an average FPKM of 207 for Gp1r and 9.0 for Sstr3 in mouse purified β cells. Moreover, we previously showed that the mouse insulinoma β-cell line MIN6 do not express RXfp4 (Ang et al. 2017). Similarly, human whole pancreatic islets display no detectable RXFP4 transcripts (Eizirik et al. 2012), and 11 preparations of human FACs-purified β-cells show negligible RPKM values ranging from 0.0 to 0.11 (Nica et al. 2013). An FPKM or RPKM value greater than 1.0 is considered significant in samples of RNA derived from homogeneous cell populations (Hebenstreit et al. 2011, Adriaenssens et al. 2016), and in the same human preparations, the RPKM values for Gp1r ranged from 25.7 to 73.2 and those for SSTR3 ranged from 7.7 to 21.8. Thus, it is highly unlikely that pancreatic islets in mouse or human are a physiologically relevant target for INSL5 action.

Transcriptomic analyses by others have revealed a slightly different pattern of RXFP4 expression between human and mouse tissues. Whereas in human, RXFP4 is expressed in duodenum, small intestine, colon and rectum
but not in lung, in mouse Rxfp4 is expressed in colon and lung but not in duodenum or small intestine (Yue et al. 2014, Uhlen et al. 2015) (Supplementary Fig. 6). It is also noteworthy that the RXFP4 amino acid sequence is highly conserved in human, monkey (97% homology), cow (85% homology) and pig (87% homology) but less so in mouse (74% homology), and Rxfp4 is a pseudogene in rat (Chen et al. 2005). Thus, RXFP4 may have different and perhaps more evolved biological functions in humans compared to mice. This also highlights the importance of using a human model such as NCI-H716 cells when studying the biological functions of INSL5 acting on RXFP4.

The effects of INSL5 signalling were examined on GLP-1 release from NCI-H716 cells. In general, we found that the response window for GLP-1 secretion in NCI-H716 cells was small but detectable, in agreement with a recent study showing a weak but comparable GLP-1 response in the same cells (Kuhre et al. 2016). In the current study, acute INSL5 treatment had no significant effect on basal GLP-1 release or on release in response to the secretagogues carbachol or insulin, but INSL5 did inhibit GLP-1 release in response to the adenyl cyclase activator forskolin. Inhibition of GLP-1 secretion by INSL5 is consistent with activation of Goαs-coupled RXFP4, inhibition of adenyl cyclase activity and a decrease in cAMP production (Ang et al. 2017), since cAMP is upstream of GLP-1 secretion in L-cells (Reimann et al. 2012). For instance, stimulation of either the Goαs-coupled somatostatin receptor SSTR5 or the galanin receptor GALR1 inhibits GLP-1 secretion (Chisholm & Greenberg 2002, Psichas et al. 2016).

Physiologically, the INSL5-RXFP4 system may constitute an L-cell feedback mechanism that inhibits GLP-1 secretion at times when the hormone is not required i.e. during the fasting state and/or at the end of the fed-state when the glucose-lowering action of GLP-1 is no longer required. Consistent with this notion, plasma INSL5 levels peak during fasting and are suppressed following food intake (Grosse et al. 2014), a trend that opposes that of GLP-1 (Hornnes et al. 1980, Ørskov et al. 1996). The inhibitory action of INSL5 on GLP-1 secretion suggests a possible autocrine/paracrine mechanism resembling that of somatostatin (Chisholm & Greenberg, 2002). Nevertheless, the inhibition of GLP-1 secretion by INSL5 is modest in NCI-H716 cells (~30% inhibition of forskolin-induced GLP-1 release). Given that regulation of GLP-1 release in L-cells is complex and governed by multiple signalling mechanisms including membrane depolarisation and Ca2+ influx, as well as cAMP (Reimann et al. 2006), it is possible that the inhibitory effect of INSL5 on GLP-1 release in this system may be less significant than that observed in a physiological setting. In addition, the mechanisms that control INSL5 release – whether by neural, endocrine, paracrine and/or autocrine pathways – are still unknown.

Interestingly, chronic INSL5 pre-treatment resulted in a somewhat unexpected increase in basal GLP-1 secretion that could not be explained by an increase in proglucagon content. One speculative mechanism for this observation is a phenomenon known as heterologous sensitisation of adenyl cyclase by Gαs-coupled receptors (see review by Brust et al. 2015). Indeed, a number of Gαs-coupled receptors including the δ-opioid receptor, μ-opioid receptor and dopamine D2 receptor display a paradoxical enhancement of basal and/or Gs-mediated cAMP production following prolonged agonist stimulation (Watts et al. 2001, Clark et al. 2004, Zhang et al. 2006). Therefore, it is possible that prolonged INSL5 stimulation could lead to heterologous sensitisation of adenyl cyclase to produce enhanced cAMP signalling in NCI-H716 cells, and hence, a resultant increase in GLP-1 secretion. In addition, as demonstrated in this study, INSL5 activates ERK1/2 and AKT signalling pathways both of which have been implicated in stimulation of GLP-1 secretion from L-cells (Lim et al. 2009, Gagnon et al. 2015). Thus, we speculate that acute INSL5 treatment inhibits GLP-1 secretion by coupling to Gαs proteins, whereas chronic INSL5 treatment potentiates the secretory capacity of L-cells by sensitisation of adenyl cyclase and/or activation of ERK1/2 and AKT signalling pathways, i.e. INSL5 appears to play a role in mediating both short- and long-term L-cell function.

Although transformed cell lines are relatively easy to grow and maintain compared to isolated primary cells, there are caveats to be considered when using them. NCI-H716 and GLUTag are derived from intestinal carcinoma cells that may not necessarily reflect primary L-cells (Kuhre et al. 2016). Indeed, both cell lines produce and secrete high levels of GLP-1 and GLP-2 but, unlike primary L-cells, both also produce somatostatin (SST) even though SST-producing and GLP-1-producing cells are thought to have arisen from different stages of enteroendocrine lineage commitment (Egerod et al. 2012, Kuhre et al. 2016). Furthermore, NCI-H716 cells reflect neither proximal nor distal primary L-cells since they are undifferentiated in nature (Park et al. 1987) and do not produce nor secrete CCK or PYY (Kuhre et al. 2016). In addition, regulation of the proglucagon gene in these cells differs from other systems (Cao et al. 2003). In spite of these limitations, NCI-H716 cells do express high levels of the proglucagon gene GCG as well as RXFP4, but INSL5 poorly (Fig. 5B). A more physiologically relevant model, such as mixed primary
intestinal cell culture (Reimann et al. 2008) would be necessary to clarify the role of INSL5 in primary L-cells.

The current study revealed no Rxfp4 expression in GLUTag cells and no INSL5-stimulated cell signalling, unlike a previous report (Luo et al. 2015). Discrepancies in gene expression between GLUTag cells in different laboratories may reflect genomic and transcriptomic variability, possibly arising from differences in culture methods and conditions (Fratini et al. 2015). Thus, in our hands, GLUTag cells were not an appropriate model to study the role of RXFP4 signalling on GLP-1 release. Furthermore, in our hands, L513 cells were unresponsive to INSL5 treatment even though the cells did express RXFP4. It may simply be a case of the mRNA being expressed but not the protein for RXFP4. Another possible explanation is that gel-forming mucus secreted from these cells may actually form a physical barrier at the cell surface that prevented INSL5 access to membrane-bound RXFP4 or even adsorbs peptide but allows small molecules to diffuse across and activate their receptors. In addition, the lack of INSL5 response may be explained by a polarised RXFP4 localisation at the basolateral membrane of L513 cells that is inaccessible under the current conventional culture method. Indeed, bile acids stimulate GLP-1 secretion predominantly by accessing the receptor GBP1 located at the basolateral surface of L-cells (Brighton et al. 2015).

In vivo, Insll5−/− mice exhibit mild impairment in glucose metabolism compared to WT mice as demonstrated in glucose tolerance tests (Burnicka-Turek et al. 2012, Lee et al. 2016). Interestingly, however, this metabolic phenotype is not observed in Rxfp4−/− mice (Grosse et al. 2014). In humans, single nucleotide polymorphisms of RXFP4 are associated with increased body mass index (BMI) and obesity (Munro et al. 2012), indicating that INSL5-RXFP4 may have important roles in controlling energy balance. Here, our results provide further evidence for a metabolic function of INSL5 by showing that this peptide activates multiple signalling pathways in the human L-cell model NCI-H716 cell line and functions to regulate GLP-1 secretion. Nevertheless, a previous study reported that plasma GLP-1 levels were unaltered in Insll5−/− mice compared to WT mice at baseline and following oral glucose administration (Burnicka-Turek et al. 2012). However, these mice lacked the Ins15 gene since birth and therefore in theory could have developed compensatory mechanisms on L-cell secretory function that substitute for the loss of Ins15. To this end, it would be useful to investigate the effect of exogenous INSL5 administration and also the effect of switching on Ins15 gene expression e.g. in a tetracycline inducible system in a mouse model, on plasma GLP-1 levels.

In conclusion, we have shown that (1) Ins15 is expressed in enteroendocrine L-cells in mouse colon and its receptor Rxfp4 is expressed in the various tissues including the GI tract and (2) INSL5 activates multiple signalling pathways in the human L-cell model NCI-H716 cell line that expresses RXFP4 and regulates GLP-1 release differentially depending on the duration of agonist exposure. Understanding of the underlying signal transduction mechanisms stimulated by INSL5 in a biologically relevant cell culture model is a critical step in elucidating the function of this novel gut hormone.

Supplementary data
This is linked to the online version of the paper at https://doi.org/10.1530/JME-17-0152.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

Funding
This work is supported by an Australian National Health and Medical Research Council (NHMRC) program grant (1055134; RJB). S YA is a recipient of the Monash Graduate Scholarship (MGE) and Monash International Postgraduate Research Scholarship (MiPRS). D SH is supported by a NHMRC Career Development Fellowship (545952). Research at the Florey was supported by an ARC Linkage grant to RADB (LP120100654) and by the Victorian Government Operational Infrastructure Support Program. R A D B is supported by an NHMRC Research Fellowship.

Author contribution statement
S YA planned and performed the experiments and wrote the manuscript. B AE provided research ideas, advised on gene expression experiments and designed hybridisation probes. D PP assisted in dissection and provided advice on immunofluorescence. R B and J D provided assistance and advice for in situ hybridisation. R A D B and M K provided research and manuscript ideas. D SH managed animals, assisted in dissection and provided research and manuscript ideas. R J S conceived the study, provided research ideas and wrote the manuscript.

Acknowledgement
The authors thank Josh Conner (Medicinal Chemistry, Monash Institute of Pharmaceutical Sciences, Monash University, Australia) for synthesising FITC-tyramide used for in situ hybridisation in this study and Cameron Nowell for excellent technical assistance.

References
Adriaenssens AE, Svedens B, Lam BYH, Yeo GSH, Holst JJ, Reimann F & Grible FM 2016 Transcriptional profiling of pancreatic alpha, beta and delta cell populations identifies delta cells as a principal target for ghrelin in mouse islets. Diabetologia 59 2156–2165. (https://doi.org/10.1007/s00125-016-4033-1)


Gustafsson JK, Navabi N, Rodríguez-Pitíreño AM, Alomran AHA, Premaratine P, Fernandez HR, Banerjee D, Sjövall H, Hansson GC & Lindén SK 2013 Dynamic changes in mucus thickness and ion secretion during Citrobacter rodentium infection and clearance. PLOS ONE 8 e84430. (https://doi.org/10.1371/journal.pone.0084430)

Halls ML, Bathgate RA, Sutton SW, Dschietzig TB & Summers RJ 2015 International union of basic and clinical pharmacology. XCV. Recent advances in the understanding of the pharmacology and biological roles of relaxin family peptide receptors 1–4, the receptors for relaxin family peptides. Pharmacological Reviews 67 389–440. (https://doi.org/10.1152/1545-2634.00947z)


Lee YS, De Vadder F, Tremaroli V, Wichmann A, Mithieux G & Backhed F 2016 Insulin-like peptide 5 is a microbially regulated peptide that promotes hepatic glucose production. Molecular Metabolism 5 263–270. (https://doi.org/10.1016/j.molme.2016.01.007)


INS5 signalling and function in NCI-H716 cells


Watts VJ, Taussig R, Neve RL & Neve KA 2001 Dopamine D2 receptor-induced heterologous sensitization of adenyl cyclase requires Gαs: characterization of Gαs-insensitive mutants of adenyl cyclase V. Molecular Pharmacology 60 1168–1172. (https://doi.org/10.1124/molpharm.60.6.1168)
