Early interactions of Salmonella enterica serovar typhimurium with human small intestinal epithelial explants

A Haque, F Bowe, R J Fitzhenry, G Frankel, M Thomson, R Heuschkel, S Murch, M P Stevens, T S Wallis, A D Phillips, G Dougan

Background: Salmonella enterica serovar typhimurium (S typhimurium) causes invasive gastroenteritis in humans, a disease involving significant penetration of the intestinal mucosa. However, few studies have been undertaken to investigate this interaction directly using differentiated human gut tissue.

Aims: To investigate the early interactions of an enteropathogenic strain of S typhimurium with human intestinal mucosa using human intestinal in vitro organ culture (IVOC).

Methods: Wild-type and mutant derivatives of S typhimurium TML were used to compare interactions with cultured human epithelial cells, bovine ligated loops, and human intestinal IVOC.

Results: S typhimurium TML was shown to attach to cultured Caco-2 brush border expressing cells and cause tissue damage and fluid accumulation in a ligated bovine loop model. S typhimurium TML bound predominantly to the mucus layer of human IVOC explants during the first four hours of IVOC incubation. From four to eight hours of IVOC incubation, small but characteristic foci of attaching and invading S typhimurium TML were detected as clusters of bacteria interacting with enterocytes, although there was no evidence for large scale invasion of explant tissues. Ruffling of enterocyte membranes associated with adherent Salmonella was visualised using electron microscopy.

Conclusions: Human IVOC can be used as an alternative model for monitoring the interactions between S typhimurium and human intestinal epithelium, thus potentially offering insight into the early stages of human Salmonella induced gastroenteritis.

MATERIALS AND METHODS
Bacterial strains and media

S typhimurium TML, obtained from Microscience Ltd (Berkshire, UK), was originally isolated from a clinical case of gastroenteritis. S typhimurium 4/74 (ST4/74) is a bovine isolate. For all infection assays, except the bovine ligated loop assay, S typhimurium TML was cultured statically, and fully differentiated human gut epithelial tissue. This is important because, remarkably, to our knowledge there are no recent studies employing this human epithelial tissue. This is important because, remarkably, to our knowledge there are no recent studies employing this human epithelial tissue.

Background: Salmonella enterica serovar typhimurium (S typhimurium), are leading causes of self limiting non-typhoidal gastroenteritis in humans. Studies using the mouse, together with in vitro models such as cultured eukaryotic cells, have yielded details about the molecular and genetic events that underpin some aspects of Salmonella virulence. However, it has been relatively difficult to directly assess the contribution made by Salmonella associated virulence genes to human gastroenteritis as in vitro cultured human epithelial cells and the adult mouse cannot mimic many aspects of the pathogenesis of this human disease syndrome. Studies in some farm animal hosts, such as cattle that develop a pyrexial mucopurulent diarrhoeal disease similar to that in humans, have improved our understanding of the cellular and molecular events that occur during S enterica associated gastroenteritis. However, we felt it would be instructive to examine the interactions between S typhimurium and fully differentiated human gut epithelial tissue. This is important because, remarkably, to our knowledge there are no recent studies employing this direct approach. Consequently, we utilised an in vitro organ culture (IVOC) system that has been used previously to study bacterial interactions with human intestinal epithelium to assess S typhimurium interactions with human terminal ileal epithelial tissue.

Abbreviations: C2BBe, Caco-2 brush border expressing; ELISA, enzyme linked immunosorbent assay; IVOC, in vitro organ culture; LB, Luria-Bertani; OsO4, osmium tetroxide; PBS, phosphate buffered saline; SEM, scanning electron microscopy; TEM, transmission electron microscopy

See end of article for authors’ affiliations

Correspondence to: Dr A Haque, Immunology Unit, Department of Infectious and Tropical Diseases, London School of Hygiene and Tropical Medicine, Keppel St, London WC1E 7HT, UK; ashraful.haque@lshtm.ac.uk

Revised version received 13 February 2004
Accepted for publication 17 March 2004

London WC1E 7HT, UK; Medicine, Keppel St, Medicine, Keppel St, London WC1E 7HT, UK; ..........................

.................................................................

www.gutjnl.com
antibiotic, homogenised, and the homogenate plated out on 
L agar to enumerate bacteria. Other tissue samples were 
treated in a number of different ways at the end of the 
incubation period. Samples to be analysed by scanning 
electron microscopy (SEM) were fixed in 2.5% phosphate 
buffered glutaraldehyde and post fixed in 1% aqueous 
-osmium tetroxide (OsO₄). Samples to be analysed by 
transmission electron microscopy (TEM) were fixed in 2.5% 
glutaraldehyde/2% paraformaldehyde in 0.1 M sodium cacodylate, and post fixed in 1% aqueous OsO₄. Samples to be 
alysed by light microscopy were fixed in 3.7% formaldehyde in phosphate buffered saline (PBS), dehydrated, 
paraffin embedded, and sectioned at 4 μm thickness, before 
being stained with haematoxylin and eosin. Areas of 
bacterial/epithelial cell interaction ("foci of infection") were 
detected by microscopic analysis of this tissue. A minimum of 
50 villus sections from five non-consecutive tissue sections 
were counted per sample.

Bovine ligated ileal loop assay
Twenty eight day old Friesian bull calves were anaesthetised 
with pentobarbital (0.44 mg/kg body weight) for the dura-
tion of the experiment. The abdominal wall was opened by a 
midline incision, the distal ileum was exteriorised, and the 
intestinal lumen was flushed with PBS. Loops, 5 cm in 
length, with 1 cm spaces in between them, were constructed 
using surgical silk. Prepared inocula (5 ml) in LB broth were 
injected into each loop, and control loops injected with sterile 
LB broth. The loops were returned to the abdominal cavity 
and the wound was repaired. Twelve hours after inoculation, 
the ileum was exteriorised, the loops cut out, and the tissue 
fixed in 2.5% phosphate buffered glutaraldehyde, and post-
fixed in 1% aqueous OsO₄, for subsequent analysis by SEM.

Caco-2 brush border expressing epithelial cell 

invasion assay
Caco-2 brush border expressing (C2BBe) cells were main-
tained in Dulbecco’s modified Eagle’s medium with 4 mM 
1-glutamine, adjusted to contain 1.5 g/l sodium bicarbonate, 
4.5 g/l glucose (90%), and fetal calf serum (10%) supple-
mented with 0.01 mg/ml human transferrin. Cells were 
grown to confluence and differentiated for 14 days before 
use in invasion assays. Monolayers were infected in triplicate 
well plates at a multiplicity of infection of 10 with bacteria that 
had been harvested from LB broth cultures by centrifugation, 
washed once in PBS, and diluted to the desired concentration 
in tissue culture medium. Infected monolayers were cen-
trifuged at 250 g for five minutes and then incubated for 
20 minutes at 37°C/5% CO₂. After such time, monolayers 
were extensively washed and incubated at 37°C/5% CO₂. At 
various time points, culture supernatants were collected, and 
monolayers were washed, lysed with detergent (0.1% Triton
6100), and the lysate diluted and plated out to determine bacterial viable counts.

RESULTS
Phenotypic characterisation of *Salmonella typhimurium* TML interactions with cultured human Caco-2 cells and in bovine ligated loop assays

To our knowledge, no other studies have yet been published describing the interaction of *Salmonella typhimurium* with explanted human intestinal tissues. Consequently, it was important to carefully characterise and validate the pathogenicity and invasiveness of the *Salmonella typhimurium* strain selected for the study. *Salmonella typhimurium* TML was originally isolated from a case of human gastroenteritis and has been shown to be enteropathogenic when tested in rabbit ligated ileal loops. More recently, mutant derivatives of the same isolate utilised in this study were shown to colonise the human intestine of volunteers. Initially, the ability of *Salmonella typhimurium* TML to interact in vitro with the immortalised epithelial cell line, C2BBe, was investigated. C2BBe cells form a polarised monolayer with an apical brush border morphologically comparable with that of the human colon. *Salmonella typhimurium* TML associated readily with C2BBe cells (∼7% of the original inoculum after two hours of incubation) and was not dislodged by extensive washing of monolayers prior to detergent lysis (fig 1). This suggests that bacteria were binding strongly to the epithelial cell surface and/or were invading the cells.

The enteropathogenicity of *Salmonella typhimurium* TML in vivo was then investigated using a bovine ligated ileal loop assay as this is one of the best models for studying *Salmonella* induced enteritis in non-human species. SEM analysis of control loops, which had been injected with LB broth into the lumen, demonstrated good preservation of gut mucosal architecture, with no evidence of damage to villi lining the gut (fig 2A). In contrast, SEM analysis of loops injected with either *Salmonella typhimurium* TML into the lumen or a well characterised bovine virulent strain, *Salmonella typhimurium* 4/74, showed extensive damage to villi lining the gut (fig 2B). Accumulation of fluid, secreted into ligated ileal loops, is a reliable indicator of the enteropathogenicity of *Salmonella* serovars. There was no significant fluid accumulation in loops injected with LB broth (fig 2C). In contrast, both the positive control strain *Salmonella typhimurium* 4/74 and *Salmonella typhimurium* TML induced fluid secretion responses (fig 2C).

### Interaction of *Salmonella typhimurium* TML with human terminal ileal epithelial tissue maintained by IVOC

Terminal ileal biopsies, maintained by IVOC, were incubated for two hours and four hours with *Salmonella typhimurium* TML, and then washed to remove mucus, revealed no obvious damage or bacteria on apical epithelial cell surfaces.

---

**Figure 3** *Salmonella enterica* serovar *typhimurium* (*S* *typhimurium*) TML adheres to mucus overlying human terminal ileal epithelial tissue.

(A) Scanning electron microscopy (SEM) analysis of uninfected human terminal ileal epithelial tissue, incubated by in vitro organ culture (IVOC) for four hours, revealed a mosaic appearance of the apical surface of gut enterocytes unobstructed by mucus. (B) SEM analysis of human terminal ileal epithelial tissue, incubated by IVOC for two and four hours with *S* *typhimurium* TML, revealed large numbers of uniform rod-shaped bacilli, ~1.5 μm in length, located in a mucus layer covering the tissue. (C) SEM analysis of human terminal ileal epithelial tissue, incubated by IVOC for two and four hours with *S* *typhimurium* TML and then washed to remove mucus, revealed no obvious damage or bacteria on apical epithelial cell surfaces. (D–F) Immunostaining of 4 μm thick paraffin sections from four hour IVOC samples, uninfected (D) or inoculated with *S* *typhimurium* TML (E, F). Staining was performed using inhouse polyclonal sera from rabbits immunised with *S* *typhimurium*. Extensive brown peroxidase staining (arrows) was observed in mucus (M), overlying villi but not in epithelial cells (E), or lamina propria (LP) of the villi themselves. (F) Higher magnification (100×) revealed individual bacilli in mucus (M), overlying epithelial cells (E), and staining for brown peroxidase stain.

---

www.gutjnl.com
SEM to be associated with a mucus layer overlying the tissue (fig 3B). Interestingly, no mucus layer was discernible by SEM above uninfected IVOC samples maintained for two or four hours, suggesting that infected samples differed from uninfected samples in the quantity of mucus they secreted (fig 3A). This suggests that mucus accumulation could be stimulated by the presence of the Salmonella bacteria on the IVOC sample. Importantly, no bacilli-shaped structures were seen on uninfected control tissues, suggesting that commensal gut flora from the patient did not present a contamination problem in these studies (fig 3A). SEM analysis of the biopsies from six patients incubated for either two or four hours, and whose mucus had been washed off prior to glutaraldehyde fixation, revealed no obvious cases (0/6) of epithelial cell damage or clear evidence of Salmonella induced membrane ruffling at these early time points compared with unoinoculated control tissue (fig 3C). Immunohistochemical analysis of paraffin embedded tissue sections using polyclonal rabbit antisera directed against S typhimurium demonstrated strong positive staining of bacilli in the mucus above infected samples (fig 3E, F) but with little obvious staining associated with villi of either uninfected control samples (fig 3D) or villi of infected samples (fig 3E). This suggested that after two and four hour incubations, the vast majority of S typhimurium TML were located in a freshly secreted mucus layer above tissue explants.

### Table 1  Gentamicin resistant Salmonella enterica serovar typhimurium (S typhimurium) TML following incubation with in vitro organ culture

<table>
<thead>
<tr>
<th>Patient No</th>
<th>No of gentamicin protected S typhimurium in uninfected control tissue (cfu/mg of tissue)</th>
<th>No of gentamicin protected S typhimurium in infected tissue (cfu/mg of tissue)</th>
<th>% Gentamicin protected S typhimurium (original inoculum = 1.25-10^6 cfu/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>538</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>667</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>481</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>515</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1451</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4083</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2407</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>681</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4  Salmonella enterica serovar typhimurium (S typhimurium) TML interacts at discrete foci with the brush border of human terminal ileal epithelium. Human terminal ileal epithelial tissue samples from 11 patients were incubated by in vitro organ culture (IVOC), either as uninfected controls (A) or with S typhimurium TML for four hours (five cases) (B), six hours (three cases) (C), or eight hours (three cases) (D). (B) Tissue sections were stained with haematoxylin-eosin and then analysed by light microscopy to search for areas along the apical surface of the epithelial cell monolayer where bacteria appeared closely associated with the tissue. Such areas were termed “foci of interaction” (F) (C, D). (E) Data depict the mean (SD) number of “foci of interaction” observed on 4 µm thick villus sections.
Evidence provided by light and electron microscopy studies indicated that most S. typhimurium TML bacteria were associated with mucus after four hours of incubation with IVOC. However, it was possible that cellular invasion could have occurred but at a much lower frequency than that observed in experiments using C2BBe cells (fig 1) or in bovine loop assays (fig 2). In order to assess cellular invasion, terminal ileal biopsies from four patients, on four separate days, were incubated with S. typhimurium TML for four hours. After this time, gentamicin protection assays were performed to determine the extent of cellular invasion. The number of gentamicin protected bacteria ranged from 481 to 4083 cfu/mg of tissue, with a mean of 1353 cfu/mg (table 1).

Importantly, no gentamicin resistant bacteria were detected in uninfected control samples. Inoculum per mg of tissue was approximately 1.25×10⁶ cfu/mg. Thus the extent of cellular invasion detected in this assay after four hours of incubation ranged from 0.04% to 0.3% of the original inoculum, which was considered to be extremely low in comparison with similar assays performed with cultured epithelial cells.

In order to visualise bacteria that had avoided gentamicin killing, possibly by acquiring an intracellular niche, inoculated and uninoculated tissue samples were incubated in IVOC for 4, 6, or 8 hours, and then processed, sectioned, and stained for analysis by light microscopy. It was noted that the condition of inoculated tissue, observed in terms of villus morphology and epithelial cell layer integrity, remained well preserved even eight hours after incubation with S. typhimurium TML (fig 4A). IVOC tissue sections were examined by light microscopy to locate any areas of the epithelium where bacteria appeared to be adherent or intracellular (fig 4A–D). Such foci of interaction were searched for on tissue from five patients which had been incubated with S. typhimurium TML for four hours on separate days. In agreement with SEM studies it was noted that in 4/5 cases no obvious interaction between bacteria and the brush border was observed and the vast majority of bacteria were situated in mucus above the apical epithelial surface (fig 4B). However, in all samples incubated for either six hours (3/3 cases) or eight hours (3/3 cases), clear foci of interaction (both bacterial adhesion and invasion) were more readily observed (fig 4C, D). At six hours post inoculation, the frequency of bacterial foci of interaction ranged from 0.14 to 0.42 foci per villus section (fig 4E). At eight hours post inoculation, the frequency with which bacterial foci of interaction were observed ranged from 0.38 to 0.89 foci per villus section (fig 4E). With 2/3 biopsies where S. typhimurium TML had been incubated with human distal ileal tissue for eight hours, the number of foci of bacterial/epithelial interactions observed on a 4 μm thick slice through a villus approached a frequency of 1. Foci of interaction, particularly sites of epithelial cell invasion and membrane ruffling, were also observed by TEM (fig 5B) where the ordered arrangement of microvilli and the glycolcalyx layer normally observed at the apical surface of terminal ileal epithelial cells in uninfected tissue (fig 5A) appeared significantly disrupted.

**DISCUSSION**

No published studies to date have investigated the interaction of invasive *Salmonella* with fully differentiated human gut mucosal tissues. Thus we know very little about the early events associated with invasive human *Salmonella* disease and have to rely on information gleaned from studies utilising in vitro cultured epithelial cells, murine infections, or comparative studies with farm animal species. Consequently, to investigate the early events that occur during *Salmonella* interaction with fully differentiated human terminal ileal epithelial tissue, we utilised a previously established IVOC culture system. Initially, we verified the enteropathogenicity of *S. typhimurium* TML using two established model systems, C2BBe cells and bovine ligated ileal loops. *S. typhimurium* TML associated strongly with C2BBe monolayers. Therefore, we concluded that *S. typhimurium* TML was invasive and enteropathogenic in C2BBe cells and bovine ligated ileal loops, respectively.

We observed that when human terminal ileal epithelial tissue was exposed in many independent experiments to *S. typhimurium* TML rapid large scale invasion of enterocytes did not occur. Rather, the kinetics of this invasion appeared to be much slower and limited in comparison with those observed in previous in vivo studies. Although invasion levels were low, large numbers of bacteria were present in mucus overlying human IVOC brush border membranes two hours post infection and only infrequent interaction of bacteria with epithelial cell surfaces were apparent four hours post...
infection. The mucus layer was only apparent in *S. typhimurium* TML infected IVOC samples and is likely to be freshly synthesised in response to infection. Thus this mucus layer may be inhibiting bacterial interaction with host cells. It was not until later time points that bacteria/epithelial cell interactions were readily observed, and consistent with this, the gentamicin protection assays suggested only low levels of invasion of the tissue had occurred at four hours post infection. The reasons for the comparatively low levels of invasion in IVOC are unclear. Another potentially significant difference between IVOC compared with infection in vivo is that the IVOC system does not facilitate recruitment of cells such as neutrophils or dendritic cells. Recruitment of neutrophils and other cells of the immune system during an in vivo infection could promote local cytokine production, inflammation, and potentially tissue damage. Dendritic cells have been shown by others to provide an alternative pathway for penetration of the mucosal brush borders by *Salmonella*.

It is also possible that the in vitro conditions utilised in IVOC could affect expression of genes influencing invasion, such as those encoding the *Salmonella* pathogenicity island-1 type III secretion system invasion apparatus. A further explanation for the low levels of invasion observed in this study could be the lack of M cells in the tissue used. It would have been interesting to study the interactions of *S. typhimurium* TML with human M cells located in lymphoid follicle associated intestinal epithelium to assess the role of M cells in *Salmonella* invasion of human intestines. However, such explanted tissue was seldom available, and therefore extensive studies were not undertaken. However, preliminary studies using lymphoid follicle associated terminal ileal epithelial tissue did not suggest preferential invasion of follicle associated epithelium (data not shown).

By using the IVOC system to study the interactions of *S. typhimurium* with human gut epithelial tissue, we have provided evidence of bacteria/epithelial cell interaction, cellular invasion, and membrane ruffling. For these reasons, we believe that the IVOC system is consistent with other models of *Salmonella* epithelial cell interaction.23–25

Interestingly, IVOC maintained tissue continues to produce a mucus layer during culture and this provides a novel model to monitor the impact of mucus on *S. typhimurium* interaction with enterocytes. Thus generation of mucus and the appearance of membrane ruffles suggests that explanted cells are stimulated to express novel enzymes and cell pathways on exposure to *S. typhimurium*. Thus in the future, it might be possible to use the IVOC system to monitor aspects of the early host gene response to *Salmonella*. In support of this, we have measured levels of interleukin 8 associated with IVOC maintained tissue incubated with *S. typhimurium* TML and have found preliminary evidence for induction of interleukin 8 expression after *S. typhimurium* infection (our unpublished data). In further experiments it might be possible to utilise DNA microarrays combined with laser dissection microscopy to improve the scope of such gene expression studies.

In conclusion, we believe that the IVOC system provides an additional valuable alternative model for studying the early events of *Salmonella* associated gastroenteritis in the human intestine. IVOC offers the advantage that the infecting bacteria encounter populations of organised and fully differentiated human intestinal cells rather than homogenous monolayers of cells. This model could be further exploited in the future to look at a range of different *Salmonella* serovars and mutant derivatives.

ACKNOWLEDGEMENTS

This work was supported by the Wellcome Trust, by a grant from the EU, and by a DEFRA fellowship award.

**Authors’ affiliations**

A Haque, F Bowe, G Frankel, G Dougan, Centre for Molecular Microbiology and Infection, Department of Biological Sciences, Imperial College of Science, Technology, and Medicine, London, UK

R J Fitzhenny, M Thomson, R Heuschkel, S Murch, A D Phillips, Centre for Paediatric Gastroenterology, Royal Free Hospital and University College Medical School, London, UK

M P Stevens, T S Wallis, Institute of Animal Health, Compton, Berkshire, UK

**REFERENCES**


www.gutjnl.com

Gut: first published as 10.1136/gut.2003.037382 on 10 September 2004. Downloaded from...

EDITOR’S QUIZ: GI SNAPSHOT

A rare cause of gastrointestinal bleeding in a patient with hyper-IgE syndrome

Robin Spiller, Editor

Clinical presentation
A 36 year old man was referred to our hospital with signs of gastrointestinal bleeding. He presented with melaena, pallor of the skin, and general weakness, worsening over the last three weeks. Vomiting was absent. The patient has been known to suffer from hyper-IgE syndrome, a primary immunodeficiency disease causing recurrent bacterial infections. During the history of the present illness, the patient described intermittent stool irregularities with dark to black colour without fresh blood for six month as well as painful bowel movements.

Laboratory values were significant for severe anaemia (haemoglobin 5.0 g/dl) and mild elevation of parameters reflecting inflammation (white blood cell count 13 900/μl, C reactive protein 2.8 mg/dl).

The patient underwent gastroscopic examination showing flat healing defects of 4–12 mm in the whole circumference of the descending duodenum as well as thickened folds in this area. The lesions did not present with any signs of bleeding. Therefore, colonoscopy was performed the following day.

Question
What conclusions would you draw from these colonoscopy findings (fig 1)?
See page 1436 for answer
This case is submitted by:

M Götzberger, A Schlesinger, M Dauer, W Heldwein
Medizinische Klinik-Innenstadt, Klinikum der Universität München, München, Germany

A Jansson, E Renner, B H Belohradsky
Haunersche Kinderklinik, Klinikum der Universität München, München, Germany

Correspondence to: Dr M Götzberger, Klinikum der Universität München, Medizinische Klinik-Innenstadt, Ziemssenstr 1, D-80336 München, Germany; manuela.goetzberger@med.uni-muenchen.de
doi: 10.1136/gut.2003.032011

Figure 1 Endoscopic view of the colon.