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ORIGINAL ARTICLE

Intestinal damage in enterohemorrhagic *Escherichia coli* infection

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Abstract Enterohemorrhagic *Escherichia coli* (EHEC) infection leads to marked intestinal injury. Sigmoid colon obtained from two children during EHEC infection exhibited abundant TUNEL-positive cells. To define which bacterial virulence factors contribute to intestinal injury the presence of Shiga toxin-2 (Stx2), intimin and the type III secretion system were correlated with symptoms and intestinal damage. C3H/HeN mice were inoculated with Stx2-producing (86-24) and non-producing (87-23) *E. coli* O157:H7 strains and 86-24 mutants lacking *eae*, encoding intimin (strain UMD619) or *escN* regulating the expression of type III secretion effectors (strain CVD451). Severe symptoms developed in mice inoculated with 86-24 and 87-23. Few mice inoculated with the mutant strains developed severe symptoms. Strain 86-24 exhibited higher fecal bacterial counts, followed by 87-23, whereas strains UMD619 and CVD451 showed minimal fecal counts. More TUNEL-positive cells were found in proximal and distal colons of mice inoculated with strain 86-24 compared with strains 87-23 and CVD451 ($p \leq 0.01$) or UMD619 ($p < 0.05$, proximal colon, $p < 0.01$, distal colon). The results show that strains 86-24 and 87-23 exhibited better colonic persistence and more symptoms, presumably due to the presence of intimin and type III secretion effectors. Extensive intestinal mucosal cell death was related to the presence of Stx2.

Keywords Enterohemorrhagic *Escherichia coli* · Shiga toxin · Intimin · *E. coli* secreted proteins · Type III secretion system

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Introduction

Enterohemorrhagic *Escherichia coli* (EHEC) infection is associated with gastroenteritis manifesting as non-bloody or bloody diarrhea, and in severe cases the development of hemolytic uremic syndrome (HUS) [1]. Intestinal damage usually leads to hemorrhagic colitis. Macroscopic and microscopic changes have been evaluated in intestinal samples obtained from patients with severe symptoms who underwent hemicolectomy, biopsy or autopsy and may reflect the most extreme cases of intestinal involvement. Pathological lesions consisted of edema, hyperemia and hemorrhage, fibrinous exudates, vascular thrombosis, mucosal necrosis, and pseudomembrane formation [2].

Animal models of EHEC infection have demonstrated gastrointestinal symptoms, such as diarrhea, and pathology in calves, gnotobiotic piglets, rabbits, and mice [3–8].

Inflammatory colitis as well as necrotizing enterocolitis have been shown in infected gnotobiotic piglets [4] and rabbits [5]. Colons from infected mice exhibited bleeding, edema and erosions, congestion of the lamina propria with thickening of the submucosa, inflammation, damaged crypts, goblet cell depletion, and necrosis [6–8].

Although the colon is the main part of the gastrointestinal tract affected during EHEC infection, the initial colonization occurs in the ileum. Using in vitro intestinal organ cultures EHEC serotype O157:H7 was found to initially colonize the villi of the distal ileum and follicle-associated epithelium of Peyer's patches [9, 10]. This is presumably followed by colonization of the colon [10]. EHEC establish attaching and effacing (A/E) lesions on the intestinal mucosa characterized by effacement of intestinal microvilli and intimate attachment to the epithelial cell. Actin polymerization in enterocytes leads to the formation of a pedestal onto which the bacteria adhere (reviewed in Nataro and Kaper [11]). This form of adherence is mediated by intimin, an outer membrane protein encoded by the *eae* gene [12, 13], by *E. coli* secreted proteins (Esps) A, B, and D secreted by a type III secretion system (T3SS) [11], by Tir (translocated intimin receptor), and the Tir-cytoskeleton coupling protein TccP [14], also termed $EspF_U$, as well as by the *esc* and *sep* genes [13]. The genes for all these factors are located on a bacterial chromosomal pathogenicity island called the LEE (locus of enterocyte effacement) [12]. EspA forms a filament via which EspB and Tir are translocated into the intestinal epithelial cell whereas EspB and EspD may form a pore in the host cell membrane through which bacterial proteins are injected into the cell [15].

The severity of EHEC infection is attributed to Shiga toxin (Stx) [16]. Stx binds to the globotriaosylceramide (Gb3) receptor on intestinal Paneth cells [17], but not to the intestinal epithelium, as these cells lack Gb3. All the same Stx induces an intestinal inflammatory response [18] and translocates across the intestinal epithelial barrier [19]. Stx may induce apoptosis of rabbit intestinal epithelial cells in vivo [20] and human intestinal cells in vitro [21].

We have previously described a mouse model of *E. coli* O157:H7 infection [6] in which mice developed gastrointestinal, neurological and systemic symptoms with histopathology of the intestines and kidneys. These mice were not streptomycin-treated so as not to diminish the commensal microflora. The aim of the present study was to investigate the presence of colonic cell death due to EHEC in human and murine infection and to correlate the expression and secretion of *E. coli* O157:H7 factors to the development of symptoms and intestinal injury using wild-type Stx-2 producing and non-producing *E. coli* O157:H7 and mutants that do not express intimin or secrete Tir, Esps A, B, and D.

Materials and methods

Intestinal tissue from patients and controls

Sigmoid colon tissue was available from two children treated at the Department of Pediatrics, Lund University Hospital for EHEC-associated HUS. Partial sigmoidectomy was carried out in both cases because of colonic perforation. One pediatric control underwent resection of a larger part of the sigmoid colon and two pediatric controls underwent colonic biopsy. These children did not have a history of hemorrhagic colitis or HUS and their tissue samples were deemed normal by the hospital pathologist. The patients as well as the pediatric controls are described in Table 1. Tissue samples from patients and controls were obtained with informed written parental consent and the study was approved by the Ethics Committee of the Medical Faculty at Lund University. The biopsy material obtained was transferred into physiological NaCl solution for approximately 30 min followed by paraformaldehyde fixation, according to hospital routines, while all surgically resected tissue was directly paraformaldehyde-fixed in the operating room. Colonic tissue was stained with hematoxylin–eosin or periodic acid Schiff and assessed by light microscopy. CD14 was detected in the human tissues by immunohistochemistry using a previously described method [22]; for details see the supplementary data (SD). Colonic tissue was also assessed by fluorescence microscopy using the terminal deoxynucleotidyl transferase (TdT)-mediated dUPT-biotin nick-end-labeling (TUNEL) assay as described below.

Mice

C3H/HeN mice were bred in the animal facilities at the Department of Microbiology, Immunology and Glycobiology, Institute of Laboratory Medicine, Lund University. Female and male mice were used at 8–16 weeks of age. The study was approved by the animal ethics committee of Lund University (protocol no. M 231-05).

Bacteria

The bacterial strains used in this study are listed in Table S1 (see the SD). The *E. coli* O157:H7 strains, 86-24 (Stx2-producing) and 87-23 (Stx non-producing) were isolated during the Walla Walla outbreak of hemorrhagic colitis and HUS in 1986 [23] and were kindly provided by A.D. O'Brien (Department of Microbiology and Immunology, Uniformed Services University of the Health Sciences, Bethesda, MD, USA). These strains were previously characterized regarding serotype, plasmid content, enterohemolysin, the presence of *stx* and *eae* genes, enter-

Table 1 Subjects investigated in this study

Subject	Sex	Age years	Clinical symptoms	Laboratory findings	EHEC diagnostics	Colon tissue obtained
Patient 1	M	9	Bloody diarrhea Renal failure Pneumonia Peritonitis[a]	Hemoglobin 66 g/L[b] Platelets 27×10^9/L[b] Creatinine 461 μmol/L[b] LDH 98 μkat/L[b]	Fecal *E. coli* O157:H7 strain *stx2, eae* positive[c] on day 14 after onset of diarrhea Bacteria had cleared from stool by day of surgery	Partial sigmoidectomy on day 27 after onset of diarrhea, day 25 after onset of HUS
Patient 2	F	10	Bloody diarrhea Renal failure Seizures Peritonitis[a]	Hemoglobin 51 g/L[b] Platelets 39×10^9/L[b] Creatinine 394 μmol/L[b] LDH 83 μkat/L[b]	Fecal isolate not obtained, serum antibodies to O157LPS negative[d] Serum IgA antibodies to EspB positive[e]	Partial sigmoidectomy on day 16 after onset of diarrhea, day 13 after onset of HUS
Control 1	F	1	Sigmoidostomy because of anal atresia	NA	NA	Area adjacent to the sigmoidostomy
Control 2	F	14	Celiac disease in remission	NA	NA	Biopsy taken to rule out IBD[f]
Control 3	M	7	Hemorrhoids	NA	NA	Biopsy taken due to gastrointestinal bleeding[f]

M, male; F, female; NA, not applicable; IBD, inflammatory bowel disease

[a]Both patients received antibiotics consisting of intraperitoneal vancomycin and tobramycin as well as intravenous meropenem at the time of colonic resection

[b]Reference values: hemoglobin 105–150 g/L, platelet count $140–400\times10^9$/L, creatinine 22–68 μmol/L, LDH (lactic dehydrogenase) <12 μkat/L

[c]Assayed as per Svenungsson et al. [52]

[d]Assayed as per Caprioli et al. [53]

[e]This patient had one episode of hemolytic uremic syndrome (HUS) following bloody diarrhea and has not had a recurrence in over 10 years. An enterohemorrhagic *Escherichia coli* (EHEC) strain was not isolated from the stool and serology was negative for antibodies to O157LPS. The patient was assumed to have an EHEC infection based on the clinical course and on the serological finding of IgA antibodies to EspB assayed as per Sjögren et al. [54]

[f]The precise region of the resected colonic tissue is, at present, unknown

ohemorrhagic *E. coli* 60-MDa plasmid, enteroaggregative *E. coli* localized adherence probe, enteropathogenic *E. coli* adherence factor, diffuse adherence *E. coli* probe, and the Vero cell assay [6]. The strains differed only in the production of Stx2 and cytotoxicity for Vero cells [6]. The isogenicity of strains 86-24 and 87-23 was determined (see SD for methodology and Table S2). The presence of the O157 serogroup antigen was confirmed by slide agglutination using an *E. coli* O157 latex test kit (Oxoid, Basingstoke, UK).

Two mutant strains based on the parental 86-24 strain were used, UMD619 with a deletion in the *eae* gene encoding intimin and CVD451 with an insertion mutation affecting the *escN* gene required for secretion of Tir and *E. coli* secreted proteins A, B, and D. As controls, these bacteria with plasmids complemented with the respective genes were used ($UMD619_{pCVD444}$ and $CVD451_{pCVD446}$). The UMD619, CVD451, $UMD619_{pCVD444}$, and $CVD451_{pCVD446}$ strains were kindly provided by J.B. Kaper (Center for Vaccine Development, University of Maryland, Baltimore, MD, USA). *E. coli* FN414 was selected as a fecal control strain since it lacked genotypic and phenotypic traits associated with Stx-producing *E. coli* [6]. Stock cultures of all strains were maintained in Luria–Bertani broth/glycerol (85/15% v/v) at −80°C until used. Strains were subcultured on tryptic soy agar plates using appropriate antibiotics (see Table S1 in the SD) at the following concentrations: tetracycline 12 μg/ml, ampicillin 50 μg/ml, and kanamycin 30 μg/ml. Before inoculation, the strains were grown in Luria broth overnight with appropriate antibiotics, harvested by centrifugation, washed twice in sterile phosphate-buffered saline (PBS pH 7.4; Medicago AB, Uppsala, Sweden), and resuspended in PBS at a concentration of 10^9 cfu/ml.

In order to enhance the virulence mice were first inoculated intragastrically with each parental strain. Colons and feces were cultured when the mice developed obvious symptoms (as described below) 2–3 days post-inoculation. Cultures obtained from the colons of sick mice inoculated with *E. coli* O157:H7 strains 86-24, 87-23, $UMD619_{pCVD444}$ or $CVD451_{pCVD446}$ were termed "INT" (standing for intestine) as listed in Table S3 in the SD. Colonic cultures of the mice inoculated with UMD619 and CVD451 were negative. A fecal UMD619 strain was isolated from one sick mouse and termed "UMD619FE" (FE standing for feces). Mice inoculated with CVD451 did not develop symptoms

during these initial experiments and the parental strain was therefore used in all experiments. The FN414 strain has previously been shown to be avirulent in this mouse model [6] and was therefore not passaged through mice. The parental strain was used.

Infection protocol

Mice were fasted for food, but not for water for 20–24 h before inoculation. Under isoflurane anesthesia (Forene Abbot, Wiesbaden, Germany) 100 μL bacterial suspension at 10^9 cfu/mL in PBS was deposited intragastrically through a soft polyethylene catheter (outer diameter, 0.61 mm; Clay Adams, Parsippany, NJ, USA) [6]. The controls received 100 μL sterile PBS. After inoculation the catheter was removed, food was reintroduced and provided ad libitum. Mice were monitored at least every 8 h and a symptom score from 0 (no symptoms) to 4 (death) was given to each mouse as presented in Table S4 in the SD. Mice were particularly examined for gastrointestinal (changes in fecal color and consistency), neurological (defined as severe symptoms and including ataxia, rigidity, spasticity, convulsions, coma), and/or systemic symptoms (ruffled fur, hunched back, reduced response upon stimulation, tremor or shivering, lethargy). After 5 days, or when evident signs of disease were observed, inoculated and control mice were sacrificed by cervical dislocation.

Fecal cultures and bacterial burden

To assess bacterial colonisation fecal cultures were collected from mice 24 h and 96 h after inoculation and cultured on tryptic soy agar plates without antibiotics (for strains 86-24INT and 87-23INT) and with appropriate antibiotics for strains UMD619FE, $UMD619_{pCVD444}$INT, CVD451, and $CVD451_{pCVD446}$INT. *E. coli* O157 serotype was identified by the latex agglutination test.

As not all strains used carried antibiotic resistance, bacterial burden was carried out by colony hybridization. For a detailed description see the SD.

Histopathological analysis

Following assessment for gross pathological changes, colonic tissue was processed for histopathological analysis. Proximal and distal colons of mice were fixed for 24 h in 4% paraformaldehyde (Sigma-Aldrich, St. Louis, MO, USA) embedded in paraffin, sectioned (3 μm), stained with periodic acid Schiff, and examined by light microscopy. To quantify inflammatory infiltrates clusters of six or more inflammatory cells were counted in the colonic tissues.

TUNEL assay

The TUNEL method was used to identify dying cells following a previously described protocol [24, 25]. For a detailed description see the SD. TUNEL-positive cells were visualized using a fluorescence microscope Nikon ECLIPSE ε 800 (Nikon, City, Japan) mounted with an Olympus DP70 camera. The software AnalySIS Image Processing, version 3.2 (Olympus Soft Imaging System GmbH, Münster, Germany) was used for quantitating labeled cells in colonic tissue within an area of 1–11 mm^2. Values were normalized and expressed as the number of TUNEL-positive cells per 100,000 μm^2 of colonic tissue.

Caspase-3 assay

The presence of activated caspase-3, as a marker of apoptosis, was investigated in mouse intestines by immunohistochemistry using SignalStain Cleaved Caspase-3 (Asp 175) IHC Detection Kit (Cell Signaling Technology, Danvers, MA, USA) as per the manufacturer's instructions.

Statistical analysis

Statistical comparison of the effects of virulence factors on symptoms in mice inoculated with the different strains and PBS controls were evaluated by the Fisher's exact test. Comparison of the number of inflammatory clusters and the number of TUNEL-positive cells in intestinal tissue of the different groups of mice was evaluated with the Mann–Whitney test. The SPSS program (version 15.0, Chicago, IL, USA) was used. $P<0.05$ was considered significant.

Results

EHEC infection leads to severe histopathological changes in the human sigmoid

Sigmoidectomy was performed in 2 patients with HUS. A thickened and necrotic area of the sigmoid colon was removed from Patient 1 exhibiting a transmural perforation. There was a deep ulceration in the adjacent tissue involving the muscularis propria and subserosa. Areas of inflammatory infiltrates and hemorrhages were visible by light microscopy as shown in Fig. 1a. The sigmoid colon was removed from Patient 2 due to a central perforation covered with fibrin exudates. Total necrosis extended throughout the entire mural wall (Fig. 1b). At the resection borders focal necrotic areas were seen with granulation tissue penetrating the muscularis propria. The tissue was hyperemic with massive inflammatory infiltrates. For comparison normal colonic mucosa from pediatric controls was examined as shown in Fig. 1d.

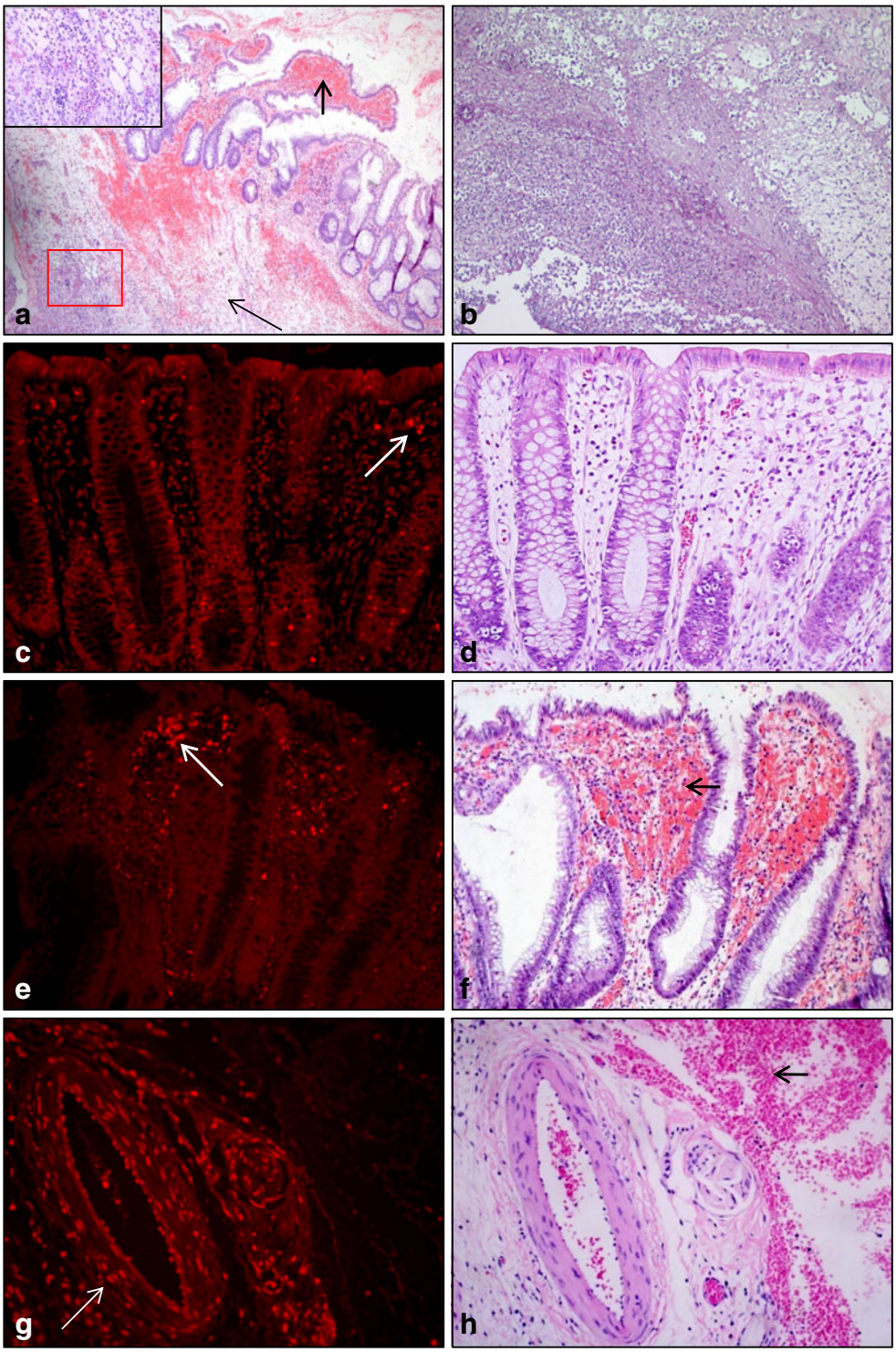

Fig. 1 Intestinal pathology in patients with enterohemorrhagic *Escherichia coli* (EHEC)-associated hemolytic uremic syndrome (HUS). Sigmoid colon was partly removed from 2 patients with EHEC infection. Panels **a**, **f**, and **h** show light microscopy from Patient 1 (as per Table 1) and panel **b** shows sigmoid colon from Patient 2 (all stained with hematoxylin–eosin). Patient tissues exhibited hemorrhages (*short arrows*), edema (*long arrow*), inflammatory infiltrates (the area in the red box at the lower left of panel **a** is enlarged in the inset) and necrosis in the colonic submucosa (visible in panel **b**). Panel **d** shows light microscopy from Control 1 stained with hematoxylin–eosin. Panels **c**, **e**, and **g** show terminal deoxynucleotide transferase-mediated dUTP nick-end labeling (TUNEL) in tissue from Patient 1 (panels **e** and **g**) and Control 1 (**c**). Abundant TUNEL labelling was detected in the lamina propria (**e**, see *arrow*) and in blood vessels (**g**, see *arrow*). Few TUNEL-positive cells were noted in the normal colonic mucosa (**c**, see *arrow*). Magnification ×50 (**a**), ×200 (**b**–**f**), ×400 (**g**, **h**)

TUNEL-positive cells in the human sigmoid during EHEC infection

Abundant TUNEL-positive nuclei were demonstrated in the lamina propria in the mucosa of the sigmoideum removed from both HUS patients (Fig. 1e and g show tissue from Patient 1, see Fig. 1f and h for adjacent hematoxylin–eosin-stained sections). TUNEL-positive cells were found in all layers of the sigmoid section. The labeled areas included intestinal cells, vascular cells as well as inflammatory cells. CD14-positive cells were found in the submucosa of sigmoid colon from Patient 1 in the same area in which multiple TUNEL-positive cells were visualized indicating the presence of macrophages and/or monocytes in these

regions (Fig. S1 in the SD). Few TUNEL-positive nuclei were noted in the colon from control tissues (Fig. 1c). CD14-positive cells were not demonstrated in the colon from Control 2 (data not shown).

The results indicate that affected areas of the sigmoid colon removed from patients with EHEC infection contain multiple TUNEL-positive cells. We therefore continued to examine which EHEC virulence factors contributed to symptoms, intestinal damage, and intestinal cell death in a mouse model.

Shiga toxin, intimin, Tir, and *E. coli* secreted proteins promote disease in mice

C3H/HeN mice (n=115) were intragastrically inoculated with *E. coli* O157:H7 strains 86-24INT, 87-23INT, UMD619FE, UMD619$_{pCVD444}$INT, CVD451, CVD451$_{pCVD446}$INT, as well as the non-virulent strain *E. coli* strain FN414. Mice were observed for gastrointestinal, neurological and systemic symptoms and signs of clinical disease were compared between mice inoculated with the various strains and PBS controls (Fig. 2). Most mice that developed symptoms demonstrated initial signs of disease within the first 24 h (Table 2). Mice that developed severe symptoms and death (symptom scores 3–4) presented with ruffled fur, hunched posture, and decreased activity followed in certain mice by neurological symptoms such as ataxia and rigidity within 2–3 days of challenge. Mice that developed milder symptoms (symptom scores 1–2) and were not sacrificed recovered spontaneously within the observation period of 5 days. The most severe symptoms developed in mice inoculated with the wild-type Stx-producing 86-24INT strain in which 20 out of 25 mice developed symptoms and 11 of the mice developed severe symptoms including neurological symptoms. The wild-type Stx-negative strain 87-23INT also led to severe systemic symptoms in 6 out of 20 mice. No neurological symptoms were observed in the latter group.

Ten out of 25 mice inoculated with strain UMD619FE developed symptoms, of which 8 developed mild symptoms and recovered. Six of the 10 mice inoculated with UMD619$_{pCVD444}$INT developed symptoms, of which severe symptoms developed in 3 out of 10 mice resembling symptoms in mice inoculated with the 86-24INT strain, as expected.

None of the 23 mice inoculated with strain CVD451 developed severe symptoms and only 7 out of 23 developed milder systemic symptoms and recovered by day 3 post-inoculation. Five out of 10 mice inoculated with strain CVD451$_{pCVD446}$INT strain developed symptoms of which two mice exhibited severe symptoms, comparable to those in mice inoculated with the wild-type strain *E. coli* 86-24INT.

None of the mice developed obvious diarrhea or visible blood in the feces, although feces were discolored in sick mice. No symptoms were seen in either the two mice inoculated with the control FN414 strain or in the PBS controls.

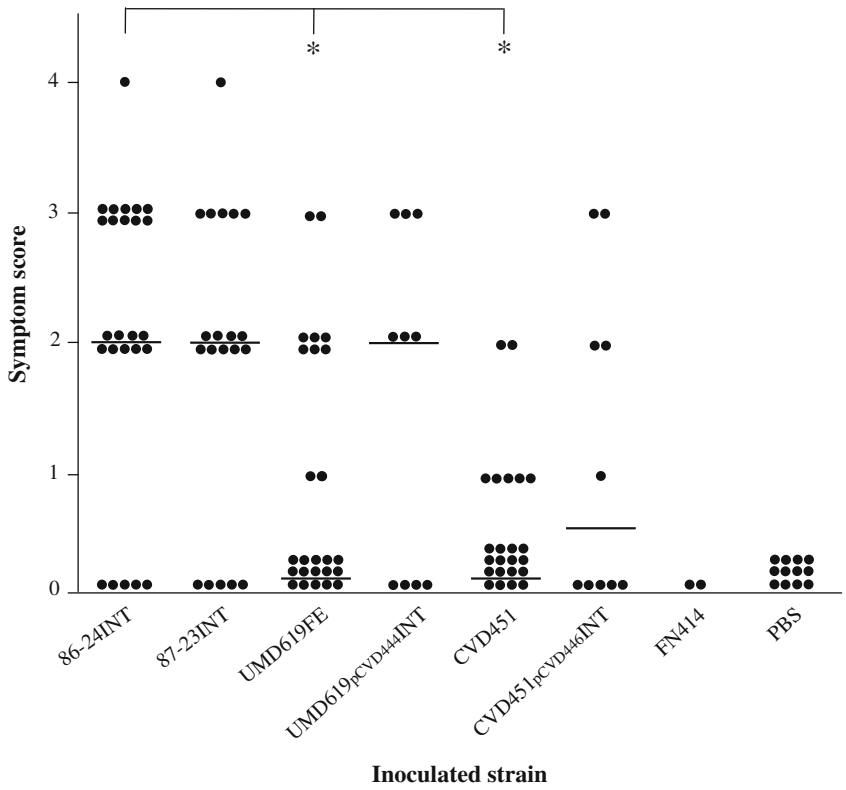

Fig. 2 Symptoms in inoculated mice. A symptom score of 0–4 (as per Table S4, see SD) was assigned to each mouse during the 5-day observation period. The highest score is shown for each individual mouse as well as medians for the group. Severe symptoms developed in mice inoculated with strains 86-24INT and 87-23INT. Few mice inoculated with the mutant strains developed severe symptoms. *P<0.01. Mice inoculated with each *E. coli* O157:H7 strain were also statistically compared with PBS controls, for 86-24INT, 87-23INT, and UMD619$_{pCVD444}$INT P<0.01 and CVD451$_{pCVD446}$INT P=0.01, for UMD619FE P<0.05, comparison with CVD451 was non-significant (P=0.07)

Table 2 Numbers of sick mice, fecal cultures, and bacterial counts in mice inoculated with each respective strain

EHEC strain	Total number of inoculated mice	Number of sick mice during the entire experiment (percentage of total)	Sick day 1	Positive fecal culture day 1		Bacterial counts CFU/mg feces on day 1	
				Symptomatic	Asymptomatic	Median	Range
86-24INT (Stx2+)	25	20 (80)	20	19	4	12,987	1,860–130,337[b]
87-23INT (Stx-)	20	15 (75)	15	13	4	1,388	134–3,827[c]
UMD619FE (*eae* mutant)	25	10 (40)	7	7	10	5	0–395[d]
$UMD619_{pCVD444}INT$	10	6 (60)	4	4	4	NA	NA
CVD451 (*escN* mutant)	23	7 (30)	7	6/6[a]	8/9[a]	0	0–744[e]
$CVD451_{pCVD446}INT$	10	5 (50)	2	2	7	NA	NA

NA, not assayed

[a] Not all mice in this group were cultured, the denominator is equivalent to the number of cultured mice in this group on day 1

[b] 5 mice

[c] 3 mice

[d] 5 mice

[e] 5 mice

The results suggest that the presence of Stx is essential for the development of neurological symptoms. The results also show that intimin contributed to symptoms and that an intact T3SS system is essential for the development of severe symptoms in this mouse model.

The effect of bacterial genotype on colonization and bacterial burden

Fecal cultures were taken from mice on days 1 and 4 after inoculation in order to address the importance of bacterial colonization and/or colonic persistence for the development of symptoms. The results for cultures taken on day 1 are summarized in Table 2 and show that most mice exhibited positive fecal cultures on day 1 regardless of the inoculated strain. Strain 86-24INT had the highest bacterial counts, followed by strain 87-23INT whereas strains UMD619FE and CVD451 had very low bacterial counts. Most mice did not have positive fecal cultures by day 4, even if symptomatic (data not shown).

Pathology in the colons of the sick mice

Proximal and distal colons were collected from 25 symptomatic mice inoculated with strains 86-24INT (n=6), 87-23INT (n=7), UMD619FE (n=4), UMD619pCVD444INT (n=3), CVD451 (n=2), CVD451pCVD446INT (n=3), and 14 asymptomatic mice 86-24INT (n=1), 87-23INT (n=1), UMD619FE (n=3), CVD451 (n=4), FN414 (n=1), and PBS controls (n=4). Colons from all symptomatic mice exhibited macroscopic hyperemia and sparsity of feces in comparison to colons from asymptomatic and control mice.

In symptomatic mice histopathological lesions exhibited predominantly inflammatory infiltrates in the distal colons of mice inoculated with strains 86-24INT (4 out of 6, indicating that 4 out of 6 mice exhibited inflammatory infiltrates), 87-23INT (1 out of 7), UMD619FE (2 out of 4), UMD619pCVD444INT (1 out of 3), CVD451 (1 out of 2), CVD451pCVD446INT (3 out of 3) (see Fig. S2a–c (SD)). A comparison between the numbers of inflammatory infiltrates in the different groups is shown in Fig. S3 (SD). Significantly more infiltrates were found in the distal colons of mice inoculated with strain 86-24INT compared with strain 87-23INT and PBS controls ($p<0.05$ for both). In addition, vascular congestion was noted in the distal colons of all sick mice inoculated with strain 86-24INT (inset Fig. S2a, SD) and with strain UMD619FE (data not shown). Distal colons were slightly hyperemic in mice inoculated with strains 87-23INT, CVD451, UMD619pCVD444INT, and CVD451pCVD446INT. Goblet cells depletion was noted in symptomatic and asymptomatic mice with no correlation with the bacterial strain (data not shown).

Histopathological examination of the proximal colons of all symptomatic mice revealed few inflammatory infiltrates in mice inoculated with 87-23INT (1 out of 7) and CVD451 (1 out of 2, data not shown). Furthermore, the interstitial space appeared shrunken, indicating dehydration in most of the sick mice (Fig. S2d, SD). Asymptomatic mice as well as mice inoculated with strain FN414 and PBS-control mice exhibited normal histology (Fig. S2e, f, SD).

Correlation of the inoculated strain with intestinal cell death

The TUNEL assay was performed in proximal and distal colons obtained from mice inoculated with strains 86-24INT (n=5 with symptom score 3, n=1 with symptom score 2), 87-23INT (n=2 with symptom score 3, n=3 with symptom score 2, n=1 with symptom score 0), UMD619FE (n=1 with symptom score 3, n=2 with symptom score 2, n=3 with symptom score 0), CVD451 (n=2 with symptom score 2, n=4 with symptom score 0) and from control mice (FN414, n=1 and PBS controls, n=4). To obtain optimal comparison, sections from the same part of the intestine (proximal or distal) were taken from one mouse from each of the five groups and placed on the same slide. The results of TUNEL are presented in Fig. 3 demonstrating TUNEL-positive cells in the mucosal epithelium of the proximal colon (Fig. 3a, b, showing tissue from mice inoculated with 86-24INT and 87-23INT respectively) and distal colon (Fig. 3c, 86-24INT) as well as in mucosa-associated lymphatic tissue (Fig. 3d, 86-24INT). In the PBS controls few TUNEL-positive cells were visualized in the proximal colon (Fig. 3e) and distal colon (not shown) as well as in the lymphatics (Fig. 3f).

Caspase-3 assay was performed in sections obtained from sick mice inoculated with strains 86-24INT (distal colons n=5, proximal colons n=3), 87-23INT, UMD619FE, CVD451, and PBS controls (distal and proximal colons n=1 in each group). Few caspase-3 labeled cells were found, which were predominantly located in the epithelium or in the lumen in extruded cells (Fig. 3g). Certain caspase-3-positive cells were also TUNEL-positive (Fig. 3h).

A comparison of the numbers of dying cells detected by the TUNEL assay in the colons of mice inoculated with the various bacteria strains is shown in Fig. 4. All mice inoculated with *E. coli* O157:H7 strains (irrespective of symptom score) exhibited more dying cells compared with PBS control mice. The most pronounced cell death was found in proximal and distal colons of mice inoculated with the wild-type Stx2-producing 86-24INT strain compared with 87-23INT (p<0.01 for both proximal and distal colon) or *escN* mutant CVD451 (p=0.01 proximal colon, p<0.01 distal colon) and *eae* mutant UMD619FE (p<0.05 for proximal colon and p<0.01 for distal colon).

Discussion

Enterohemorrhagic *Escherichia coli* (EHEC) infection may lead to severe hemorrhagic colitis with gastro-intestinal complications. The two pediatric patients with HUS described here had a prolonged course of disease and developed colonic perforation. These patients exemplify the most severe course of intestinal affliction during EHEC infection. We were able to demonstrate abundant cell death in their sigmoid colon using the TUNEL technique. From this we concluded that the cell death observed was, at least in part, due to apoptosis. Massive injury to the intestinal mucosa would allow bacterial virulence factors to gain access to the circulation. In an attempt to define which EHEC virulence factors contribute to intestinal cell death we used wild-type (Stx2-producing and non-producing) and mutated *E. coli* O157:H7 strains in a previously described mouse model [6]. The most pronounced cell death occurred in mice inoculated with the wild-type Stx2-producing 86-24INT strain. Less pronounced cell death was detected in mice inoculated with strain 87-23INT (the parent strain 87-23 was shown here to be isogenic to 86-24 apart from lacking Stx2) and in mice inoculated with strains UMD619FE and CVD451. The latter two strains exhibited reduced bacterial counts that could affect the toxin load released into the intestine. We thus conclude that intestinal cell injury was induced by Stx.

During interactions of EHEC with the intestinal commensal microflora Stx production can be induced by quorum sensing signaling [26], but also suppressed by the normal human microflora [27]. In vitro studies have shown that Stx causes apoptosis of human and murine intestinal epithelial cells in the distal colon [21, 28]. Furthermore, studies have shown that Stx may induce apoptosis in a variety of epithelial cells in vitro [29]. In addition to its effect on the intestine, Stx has been shown to have a cytotoxic effect and induce apoptosis of glomerular endothelial and epithelial cells [30, 31]. The current study indicates that these findings also apply in vivo as we found distinct differences in the degree of intestinal cell death induced by the Stx-producing 86-24INT strain compared with the Stx-negative strain 87-23INT confirming the potential of Stx to induce colonic cell death in vivo during EHEC infection.

The effect of Stx is enhanced by TNF-α, IL-1, LPS, and butyrate [31, 32]. Stx also exerts an apoptotic effect on human brain microvascular endothelial cells, even here the effect was increased by TNF-α, which sensitized cells to Stx1 [33]. TNF-α upregulates the Gb3 receptor [32]. The presence of the Stx receptor determines the vulnerability of tissue to toxin-induced damage. The Gb3 receptor has been detected in the intestine of rabbits [34] and mice [35]. In mice the receptor was demonstrated in the epithelium of the distal colon [35], although mRNA was also detected in the small intestine [36]. Gb3-null mutant mice were protected from Stx's effects indicating the importance of Gb3 expression for targeting of Stx-induced cellular damage [37]. In this study marked cell death was noted in both the proximal and distal colons of mice inoculated with the Stx2-producing strain (86-24). As the proximal colon in the

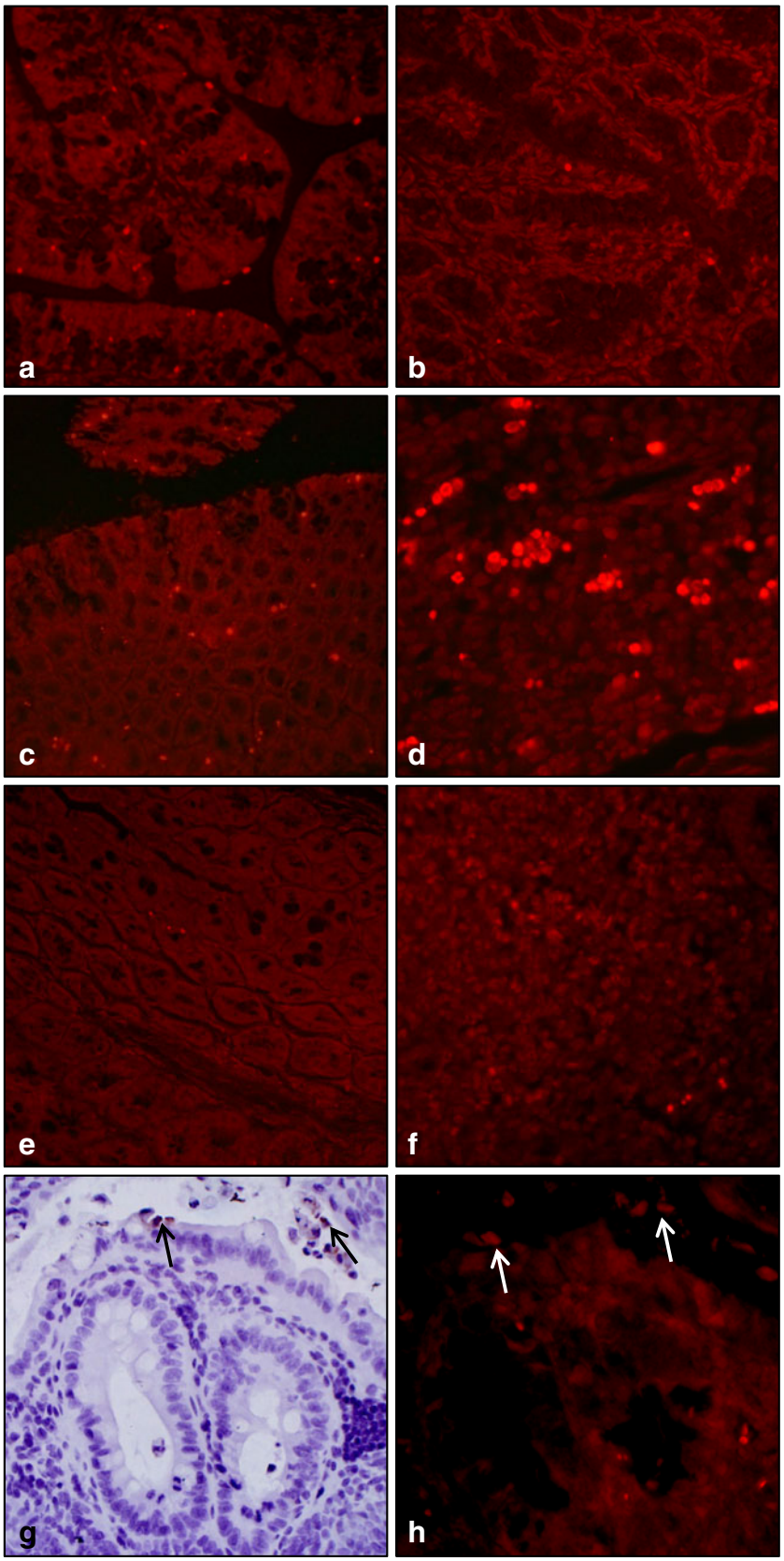

Fig. 3 TUNEL and caspase-3 labeling in colons of inoculated mice. TUNEL in **a** the proximal and **c** distal colon of mice inoculated with strain 86-24INT compared with the proximal colon of a mouse inoculated with **b** 87-23INT. The most abundant TUNEL was seen in the mucosa-associated lymphatic tissue of mice inoculated with strain 86-24INT (**d**). Few positive cells were seen in **e** the proximal colon as well as in the distal colon (not shown) and **f** lymphatic tissue of PBS control mice. Caspase-3 labeling in the epithelium and in the extruded cells in the lumen (panel **g**, see *arrows*) in the distal colon of a mouse inoculated with strain 86-24INT and the same area with TUNEL-positive cells (panel **h**, see *arrows*). Magnification ×200 (**a**, **b**, **c**, **e**); ×400 (**d**, **f**, **g**, **h**)

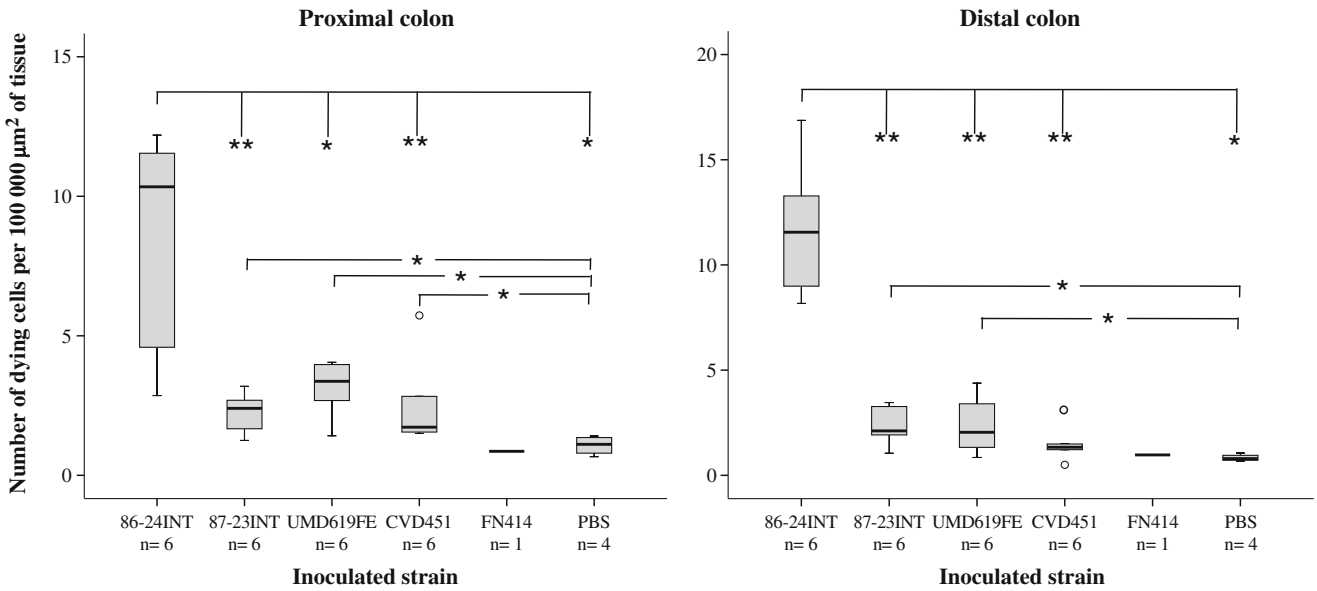

Fig. 4 Cell death in colons of inoculated mice. Cell death was assessed in sections obtained from mice inoculated with strains 86-24INT, 87-23INT, UMD619FE, CVD451, and from control mice (FN414 and PBS controls). The number of investigated mice is given under each bacterial strain. TUNEL-positive cells were quantitated within an area of 1–11 mm^2. Values were expressed as the number of TUNEL-positive cells per 100,000 μm^2 of colonic tissue. The line inside each box represents the median. The upper and lower limits of the box-plot represent the interquartile range. The upper and lower limits represent the range. Outliers are marked with *open circles*. Significantly more TUNEL-positive cells were found in proximal and distal colons of mice inoculated with strain 86-24INT compared with the other strains and the PBS controls.*$p<0.05$; **$p\leq0.01$

mouse does not bind Stx1 [35] this would suggest that not only actual Stx binding, but also secondary immune responses in the intestine could have contributed to the tissue damage.

Intimin has been implicated in the development of diarrhea in a porcine model [38]. It is necessary for colonization of the human colon by most strains of *E. coli* O157, as demonstrated using in vitro organ cultures [39]. Using the mouse ileal loop model *E. coli* O157:H7 was found to induce attaching and effacing lesions in mouse intestine [40]. The presence of intimin and its receptor Tir were essential for this interaction to occur. A previous study showed that strain UMD619 was incapable of attaching intimately to colonic epithelial cells in newborn piglets and that the complemented strain $UMD619_{pCVD444}$ regained the phenotype [38]. The results of the present investigation indicate that the same is true for this mouse model, that lack of intimin reduces bacterial counts. The Δ*eae* mutant developed fewer symptoms, as shown in Fig. 2, and the strain complemented with intimin developed symptoms similar to the wild-type 86-24INT strain, presumably because of its increased ability to colonize.

The current study showed that the *eae* and *escN* mutants exhibited markedly reduced bacterial counts, intestinal cytotoxicity, and virulence. The contributions of *eae* and *escN* to intestinal cell apoptosis have not been studied previously, although EspF, encoded on the LEE4 operon and regulated by *escN* [13], has been shown to induce host cell death via apoptosis [41]. We presume, however, that the decreased intestinal cell death observed in mice inoculated with strain CVD451 (with a mutation affecting *escN*) is primarily related to reduced bacterial counts, but cannot exclude the possible contribution of EspF to induction of cell death.

Using a *Citrobacter rodentium* model, Deng et al. studied the importance of all 41 LEE genes for the virulence of the strain in mice [13]. They conclusively showed that the entire LEE was required for full virulence and that *C. rodentium* mutants Δ*eae* and Δ*escN* did not colonize adequately or exhibit virulence. Deletion of the entire LEE4 operon encoding type III secreted proteins impaired persistence of *E. coli* O157:H7 in cattle [42] and a deletion of *espA* markedly reduced the ability of *E. coli* O157:H7 to colonize the intestines of calves [43] and bind to cultured epithelial cells and induce actin rearrangements [44]. Likewise, an *escN* mutant of EPEC, which, as in EHEC is incapable of secreting Tir, Esps A, B, and D, exhibited defective formation of attaching and effacing lesions in tissue culture cells. When complemented with the CVD446 plasmid carrying an intact *escN* gene from EPEC, the phenotype was restored [45]. The results presented herein are in agreement with these previous studies and show that an intact T3SS was essential for the development of severe symptoms.

The mouse model used here was previously developed in our laboratory [6] and does not require streptomycin treatment, as has been described for other murine models of *E. coli* O157:H7 [8, 46]. Not all mice inoculated with *E. coli* O157:H7 developed symptoms. Other murine models have circumvented the issue of bacterial inoculation by treating mice with purified Stx [47]. We believe that the model described herein is more adequate for the study of *E. coli* O157:H7-induced intestinal infection, as it would allow for quorum sensing signaling and cross-talk with the intestinal microflora to occur [26] because the mice were not pre-treated with an antibiotic. The separate contributions of the different virulence factors could be studied by genetic alterations of the parent strain. Interestingly, the Stx-negative strain 87-23INT also exhibited virulence. This observation has been made before [6] and suggests that *E. coli* O157:H7 might possess multiple virulence factors. We could, however, show that Stx2 is important for the induction of intestinal cell death. Thus, the mechanism by which strain 87-23INT induces severe symptoms in mice is presumably not entirely related to a cytotoxic effect on the intestinal epithelium.

A difference in the localization of cell death was noted when comparing human and murine intestines. In the human sigmoid colon TUNEL-positive cells were predominantly found in the lamina propria and in the vasculature, while in the mouse colon they were mostly located in the mucosa-associated lymphatic tissue and epithelial cells. These differences could be related to Stx-receptor localization, as the human intestinal microvascular endothelial cells express high levels of the receptor [48]. In addition, differences could be due to the severe and prolonged hemorrhagic colitis seen in patients, whereas mice did not develop hemorrhagic colitis. The longer time span between the onset of the infection and the removal of the colonic tissues in patients (16–27 days) in comparison to mice (2–4 days) could result in an increased cytokine response, which would be expected to contribute to the extensive damage observed in the human sigmoid colon.

Intimin-specific antibodies can be detected in sera from patients after EHEC infection [49]. Anti-intimin antibodies have been shown to protect piglets from colonization with *E. coli* O157:H7 [50]. Intimin has been studied as a potential vaccine for protection against *E. coli* O157:H7 infection. Intimin-based vaccines confer protection in immunized mice [51]. In the present study we show that patients with EHEC infection exhibited massive intestinal cell death and that the specific *E. coli* O157:H7 virulence factors addressed were all likely to contribute to this process by promoting bacterial persistence and toxin-induced intestinal cell injury. Thus, this study further suggests that *E. coli* O157:H7 adhesins and secreted proteins should be targeted as potential vaccines against bacterial colonization and intestinal injury.

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