Responses of Cattle to Gastrointestinal Colonization by 
Escherichia coli O157:H7

Pablo Nart,1,2,3 Stuart W. Naylor,1 John F. Huntley,3 Iain J. McKendrick,4 David L. Gally,2 and J. Christopher Low1*

Animal Research Group, Scottish Agricultural College, Research Division, West Mains Road, Edinburgh EH9 0PH, United Kingdom1; Zoomotic and Animal Pathogens Research Laboratory, Centre for Infectious Diseases, Chancellor’s Building, University of Edinburgh, Edinburgh EH16 4SB, United Kingdom2; Moredin Research Institute, Pentland Science Park, Bush Loan, Penicuik, Midlothian EH26 0PZ, United Kingdom3; and Biomathematics and Statistics Scotland, Edinburgh EH9 3IZ, United Kingdom4

Received 5 September 2007/Returned for modification 16 October 2007/Accepted 19 August 2008

Recent research has established that the terminal rectum is the predominant colonization site of enterohemorrhagic Escherichia coli O157:H7 in cattle. The main aim of the present work was to investigate pathological changes and associated immune responses at this site in animals colonized with E. coli O157:H7. Tissue and gastrointestinal samples from a total of 22 weaned Holstein-cross calves challenged with E. coli O157:H7 were analyzed for bacterial colonization and pathology. Five unexposed age-matched calves were used as comparative negative controls. E. coli O157:H7 bacteria induced histopathological alterations of the rectal mucosa with enterocyte remodeling. This was often associated with removal of the colonized epithelial layer. Immunogold labeling and transmission electron microscopy (TEM) showed E. coli O157:H7 bacteria on pedestals, as part of attaching and effacing lesions. These pathological changes induced a local infiltration of neutrophils that was quantified as larger in infected animals. Rectal mucosal immunoglobulin A responses were detected against the E. coli O157:H7 antigen. This work presents evidence that E. coli O157:H7 is not a commensal bacteria in the bovine host and that the mucosal damage produced by E. coli O157:H7 colonization of the terminal rectum induces a quantifiable innate immune response and production of specific mucosal antibodies.

Enterohemorrhagic Escherichia coli (EHEC) infection has emerged in the last 20 years as a cause of diarrhea that can lead to the more serious consequence of hemolytic-uremic syndrome and thrombotic microangiopathy. The majority of EHEC infections are caused by E. coli O157:H7 (24), and this serotype has been isolated frequently from cattle feces. Many human EHEC O157 infections originate, either directly or indirectly, from exposure to cattle feces (17), and a key step in protecting humans from EHEC infection is to understand and control E. coli O157:H7 colonization of cattle.

Experimental challenges have suggested a variety of colonization sites in cattle (4, 5, 12). However, more recently, the terminal rectal mucosa has been identified as the major site of E. coli O157:H7 colonization (25), and this finding has been confirmed in slaughter animals (20). From an understanding of where E. coli O157:H7 colonizes the bovine intestinal tract, there is an opportunity to examine pathological changes at the site and to determine whether these changes correlate with the development of immunological responses. The main aim of the research is to underpin methods to control this pathogen in its main animal reservoir.

A feature of E. coli O157:H7 infection is the formation of attaching and effacing (A/E) lesions, characterized by the elimination of the microvilli and intimate enterocyte attachment (7, 16). In vivo, A/E lesions are present at the terminal rectum of naturally and experimentally infected cattle, and inactivation of the type III secretion apparatus that is essential for this phenotype prevents E. coli O157:H7 colonization of cattle (27). The profound alteration of enterocyte morphology associated with A/E lesions has also been reported to be accompanied by an increase in neutrophils and eosinophils in the lamina propria of the large intestine (37), the colon and cecum (6), the gall bladder (35), and sections of ligated ileal loops (32). This type of inflammatory reaction has been described in the intestinal tract exclusively for experimental infections of gnotobiotic, neonatal, or immunosuppressed calves and in sites other than the terminal rectum. However, to date, the response to colonization at the principal colonization site has not been investigated.

Identification of the terminal rectum as the tissue targeted by E. coli O157:H7 in cattle allows the study of the pathological changes and associated innate and adaptive mucosal responses. Thus, this study had two objectives: first, to determine if E. coli O157:H7 colonization of the bovine terminal rectum induces pathological changes, in terms of both ultrastructural change to the mucosal epithelium and evidence of inflammation, and second, to investigate local immune responses to colonization. Additionally, this work aimed to confirm in a larger number of animals the previously reported findings of E. coli O157:H7 tropism for the terminal rectum.

MATERIALS AND METHODS

Animals. Fifty-four weaned Holstein-cross calves were reared conventionally on a farm before transfer to Moredin Research Institute for the experimental...
procedures (authorized by Home Office license 60/3179). The animals were between 8 and 14 weeks of age on arrival and were then penned individually for the study. Calfs were fed concentrate twice daily and had access ad libitum to hay and water. Feed, water, and bedding were provided separately for each animal to minimize cross-contamination, and each was halted to reduce the opportunity for fecal-oral transmission. Five unexposed calves of similar age, breed, and background were used as controls for the histopathological studies, and a separate group of four calves was challenged specifically for ultrastructural investigations of the colonized rectal mucosa.

**Bacterial strains.** The challenge strain of *E. coli* O157:H7 was ZAP 198 isolated from a human patient in Washington state and was used previously in experimental studies (25). ZAP 198 has been naturally cured of the verocytoxin-carrying bacteriophage, and the strain was selected for spontaneous resistance to nalidixic acid to facilitate recovery from feces and tissues. ZAP 198 possess genes for enterohemolysin, EpaA, and EspB. For the preliminary examination of adaptive responses, whole-cell extracts of *E. coli* K-12 MG1655 (2) and *E. coli* O26 ZAP 1082 (28) were used as controls in Western blots.

**Calf colonization.** Fecal samples were taken at least twice from each calf, prior to experimental challenge, and were confirmed negative for *E. coli* O157:H7 by immunomagnetic separation. The challenge *E. coli* O157:H7 strain was grown overnight in Luria-Bertani (LB) broth at 37°C with aeration and diluted in sterile phosphate buffered saline (PBS) to achieve a concentration of 10^6 CFU per animal in a total volume of 10 ml. The oral inoculum was administered to the calves via stomach tube and washed down with 500 ml of sterile PBS or by direct administration through a cannula to the rumen in six calves. Initial analysis showed that the ruminal inoculation and the challenge via nasogastric tube did not differ in terms of efficacy, and the former method was adopted. Therefore, for analytical purposes the ruminally challenged animals are included within the orally challenged group. Rectal challenge was carried out by loading a large cotton swab with the challenge inoculum, followed by direct application to the mucosal surface of the recto-anal junction (RAJ). In total, 24 calves were challenged via the rectal route and 30 by oral or ruminal administration.

Postmortem examinations were carried out with 22 animals shedding detectable levels of *E. coli* O157:H7 bacteria beyond day 14 postchallenge. Ten of these animals had been experimentally challenged with *E. coli* O157:H7 by direct rectal application and 12 by oral administration as described recently (26). Tissue samples were collected from the gastrointestinal tract for bacterial counts and histopathology. Tissue samples were taken from the rumen, jejunum, Peyer’s patch, cecum, ileoceccolic valve lymphoid patch, proximal colon, proximal colon lymphoid patch, spiral colon, and distal colon and at the proximal, mid, and distal rectum (at 20, 10, and 5 cm proximal to the RAJ) and from the RAJ itself. Luminal contents were collected from the same sites for bacterial culture, together with bile from the gall bladder.

**Site of colonization.** Out of a total of 54 animals, 46 became colonized for longer than 5 days, and a postmortem examination was carried out on 22 animals still shedding detectable levels of *E. coli* O157:H7 bacteria beyond day 14 postchallenge. Ten of these animals had been challenged by direct rectal

**RESULTS**

**Downloaded from http://iai.asm.org/ on October 15, 2017 by guest**
application and 12 by oral administration. *E. coli* O157:H7 cell counts from tissue washings of the terminal rectum were significantly higher than from tissues of the large intestine (*P* < 0.001), irrespective of the challenge route. Significantly higher counts (*P* < 0.01) were detected in the other rectal sites (5, 10, and 20 cm proximal to the RAJ) compared to counts from tissue washings of large-intestinal tissues. For the animals challenged by the direct rectal administration method, *E. coli* O157:H7 bacteria were not recovered from bile or samples of digesta from nonrectal sites that included the rumen and the small or large intestine. For the orally challenged group, *E. coli* O157:H7 bacteria were not recovered from bile (data not shown). Terminal rectal tissue collected from colonized animals allowed us to study pathological changes.

**Pathological changes at the terminal rectum.** When bacterial concentrations exceeded 10^5 CFU per cm^2*, E. coli O157:H7 bacteria could be readily detected in association with the epithelium by immunostaining and microscopy. In these positive tissues, at 15 to 21 days after challenge, the immunopositive bacteria were usually but not exclusively colonizing focal areas of the absorptive epithelium or the scarcer follicle-associated epithelium. Bacterial microcolonies ranged from those containing less than 30 bacteria to those with several hundred. The distribution of the colonies appeared random, with some microcolonies close together and others separated by large areas of noncolonized rectal tissue. In all cases, affected epithelial cells had effaced microvilli, and bacteria were intimately associated with their apical membranes. Occasionally, immunostained bacteria were present without producing major morphological alterations of the rectal epithelium. Generally, the mucosal border in foci with attached bacteria was low columnar to cuboidal (Fig. 1A and B). There was frequent exfoliation of the mucosal epithelium from the basal membrane, and bacteria were often seen in cavities of evacuated enterocytes (Fig. 1C and D). Groups of loose bacteria were also present in the mucus 40 to 100 µm from the intestinal surface and were not always associated with adherent microcolonies. On rare occasions, *E. coli* O157:H7 bacteria were also attached to areas of the squamous epithelium of the perianal region and crypts of the rectal mucosa. Rarely, an immunopositive bacterium was detectable along lymphatic lacteals of the lamina propria in areas lacking an epithelial surface. *E. coli* O157:H7 microcolonies were also detected by immunostaining at day 6, from rectal biopsy samples from three animals that were shedding >10^6 CFU g^-1 of feces of *E. coli* O157:H7 bacteria. The distribution and intimate bacterial attachment to

![FIG. 1. Histopathological changes induced by *E. coli* O157:H7 colonization at the terminal rectum of cattle. (A) Apical surface of the enterocyte partly eroded by an *E. coli* O157 microcolony (arrow). (B) A larger *E. coli* O157 microcolony causing further erosion of the cytoplasm. An *E. coli* O157 colony is illustrated (arrow). (C) Enterocytes (arrows) heavily colonized with *E. coli* O157 are shown sloughing off from the basal membrane. Bacterial aggregates surround the enterocyte. (D) A larger *E. coli* O157 microcolony is shown on the lamina propria, following the shedding of the epithelial layer. Histopathology was carried out as described in Materials and Methods.](attachment://image.jpg)
enterocytes were similar to those observed for the cases examined at postmortem at days 15 and 21 postchallenge.

The pathological changes were further examined by scanning electron microscopy, which revealed multifocal clusters of rod-shaped bacteria of up to 2 μm in length, distributed randomly over the surface of the absorptive epithelium of the rectum. TEM studies and gold particle immunolabeling allowed us to identify *E. coli* O157:H7 bacteria on pedestals as part of A/E lesions (Fig. 2A and B). Pedestal heights varied but in some cases were up to 10 μm long. Some microcolonies appeared to consist of bacteria in layers, forming a stack, and individual bacteria were observed in the process of dividing while attached to the host cells. Bacterial microcolonies were associated with different degrees of enterocyte erosion (Fig. 2C). On occasion, granulocytes were present, interspersed among enterocytes, and exuded leukocytes formed aggregations in the gut lumen (microabscesses) (Fig. 2D). Lateral and basal membrane detachment and enterocyte exfoliation were often evident but present only when the bacteria had caused enough damage to approach the cell basal nucleus.

**Cellular infiltration and inflammation.** When *E. coli* O157:H7 was isolated from mucosal washings of tissues at levels higher than 10⁵ CFU cm⁻² or from biopsy samples taken from colonized animals that had similar numbers of *E. coli* O157:H7 bacteria in feces, there was a diffuse, low to mild granulocytic focal infiltration of the lamina propria of the rectum (Fig. 3A). In the terminal rectum, a significant (*P* < 0.001) leukocytic infiltrate was present in *E. coli* O157:H7-colonized animals (mean, 6.6 ± 1.4 per 0.25 mm²) compared with controls (mean, 1.9 ± 0.9 per 0.25 mm²). However, no differences were detected between the numbers of eosinophils, mast cells, and γδ T cells (*P* > 0.65, *P* > 0.69, and *P* > 0.68, respectively) in...
coli O157:H7 at levels consistently higher than 10^4 CFU/g. Samples were taken from three animals that shed E. coli-specific mucosal antibody responses to the E. coli O157:H7. Mucosal homogenate samples showed no immune response to whole-cell extracts of the E. coli O26 or E. coli K-12 strains. Trypsinization of the E. coli K-12 and O157:H7 samples removed most of the immunoreactive material and resulted in the detection of a 14-kDa band for both strains (Fig. 4). No specific reactive bands were observed for four noninfected controls or from Western blots where the rectal mucosal homogenate was omitted (data not shown).

**DISCUSSION**

Work carried out by our group has demonstrated that E. coli O157:H7 has a tropism for the terminal rectum of cattle (25). The present study has confirmed this finding by examination of over 50 animals colonized by different challenge routes. The postmortem examination of these colonized animals also allowed the identification of minor sites of E. coli O157:H7 carriage. These sites included the rumen, small intestine, and most frequently, the proximal colon and, in particular, the lymphoid-rich tissue immediately distal to the ileocecal valve. In 2 animals out of the 54 studied, E. coli O157:H7 bacteria were distributed throughout the large intestine, given the even distribution of the bacteria throughout the fecal part. This finding is consistent with previous reports (25) and suggests that there is a different mechanism of colonization for a small number of animals, maybe due to the existence of multiple E. coli O157:H7 genetic types with different colonization strategies within one animal (11).

The postmortem and rectal biopsy materials collected from the colonized animals enabled a detailed study of the histological and ultrastructural changes associated with rectal colonization. A/E lesions were detected in animals with bacterial counts of more than 10^5 CFU/g in rectal tissues several weeks after experimental inoculation, and this is consistent with the previous finding that bacterial type III secretion system and A/E lesion formation are essential for the colonization and persistence of the organism in cattle (26). The long-term persistence is of a duration similar to the natural carriage observed for animals in field studies (1). The "shotgun" distribution of the microcolonies on the rectal mucosa may be caused by the dispersion of cells from the microcolonies into the surrounding environment, in the same manner proposed for E. coli spreading from biofilms (36) formed in response to shear forces and turbulent flow (8). In addition to A/E lesions, the major histopathological changes consisted of a reduction in enterocyte cellular width, a degeneration of cytoplasm in heavily colonized cells, and a frequent sloughing of enterocytes. These alterations were associated with a quantifiable neutrophilic response. The microscopic examination was made in animals shedding bacterial numbers similar to those animals considered super-shedders in field studies (10, 22, 34). Similar lesions have been reported in weaned calves 4 days postchallenge (7). Given the severe nature of the enterocyte changes observed, it is possible that most of the mucosal damage observed is due to enterocyte desquamation. In vitro studies have consistently reported decreased transepithelial resistance and opening of the tight junctions following E. coli O157:H7 colon-
Western blots were prepared as described in Materials and Methods. This is demonstrated with a blot using the homogenate from animal 3 (lanes labeled “Trypsinized”). Lanes marked “no primary” are controls containing E. coli O157 and K-12 preparations incubated with all the reagents, except for the rectal homogenate. Mucosal homogenates and Western blots were prepared as described in Materials and Methods.

![Image](https://via.placeholder.com/150)

**FIG. 4.** Detection of mucosal antibody responses to protein antigens of E. coli O157. Mucosal antibody was obtained from homogenates of rectal mucosa sampled from three animals that had histopathological lesions detectable by microscopy. The homogenates were used to blot whole-cell preparations of E. coli strains O157 and K-12 and, in one case, O26. Multiple E. coli O157 immunoreactive bands were detected in comparison to either E. coli K-12 or E. coli O26. Trypsin digestion of the bacterial preparations removed most of the immunoreactive material. This is demonstrated with a blot using the homogenate from animal 3 (lanes labeled “Trypsinated”). Lanes marked “no primary” are controls containing E. coli O157 and K-12 preparations incubated with all the reagents, except for the rectal homogenate. Mucosal homogenates and Western blots were prepared as described in Materials and Methods.

...


