Expression of putative virulence factors of Escherichia coli O157:H7 differs in bovine and human infections


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\textit{Escherichia coli} O157:H7 is a commensal organism in cattle, but it is a pathogen in humans. This differential expression of virulence suggests that specific virulence factors are regulated differently in human and bovine hosts. To test this hypothesis, relative real-time reverse transcription-PCR was employed to relate the expression of several putative virulence genes (\textit{eae}, \textit{espA}, \textit{stx}2, \textit{rfbE}, \textit{ehxA}, and \textit{iha}) to that of the “housekeeping” gene \textit{gnd} during natural human and experimental bovine infection with \textit{E. coli} O157:H7. We examined these genes in fecal samples from eight humans and four calves. \textit{iha} and \textit{espA} were significantly more expressed in bovine infections. \textit{rfbE} and \textit{ehxA} appeared to be more highly expressed in human infections, though these differences did not achieve statistical significance. Our results support the hypothesis that some virulence-associated genes of O157:H7 are differentially expressed in a host-specific manner.

\textit{Escherichia coli} O157:H7, a human pathogen that causes diarrhea, bloody diarrhea, and the hemolytic uremic syndrome (HUS), has acquired multiple virulence factors that might aid its pathogenicity. Principal among these are the phase-encoded Shiga toxins (Stx proteins), which inhibit protein synthesis in eukaryotic cells (41), and the \textit{LEE} pathogenicity island, which encodes products associated with formation of attaching-and-effacing lesions at the host surface (reviewed in reference 13). \textit{E. coli} O157:H7 also has a 92-kb nonconjugative plasmid that encodes several putative virulence factors, including \textit{enterohemolysin} (encoded by \textit{ehxA}, also termed \textit{hhA}) [1, 5], a member of the RTX family of exoproteins. \textit{E. coli} O157:H7 also expresses the IrgA homologue adhesin (Iha), which was recently identified as a virulence factor in uropathogenic \textit{E. coli} (16, 38).

Some of these factors can affect animal hosts. For example, \textit{E. coli} O157:H7 causes attaching-and-effacing lesions on cultured bovine cells (31) and in neonatal calves (8). Despite this, \textit{E. coli} O157:H7 is not known to cause natural disease in any host except humans. This discrepancy suggests the hypothesis that specific virulence factors of \textit{E. coli} O157:H7 are regulated differently when the bacteria are in the human rather than the bovine gut. To test this hypothesis, real-time reverse transcription-PCR (RT-PCR) was employed to examine gene expression in fecal samples from children infected with \textit{E. coli} O157:H7 and from experimentally infected calves. The resulting data support the hypothesis that virulence genes are differentially expressed in the human and bovine hosts.

**MATERIALS AND METHODS**

\textbf{Strains and media.} Bacteria were grown in a shaking incubator at 37°C in Luria-Bertani (LB) medium. When appropriate, ampicillin (100 \mu g/ml) or nalidixic acid (32 \mu g/ml) was added. Strain 86-24 is a well-studied clinical isolate of \textit{E. coli} O157:H7 (39). Strain 86-24Δ\textit{rfr} (3) was used to infect calves. ORN172(pIHA) contains \textit{iha} on a high copy plasmid (38). Shiga toxin-producing \textit{E. coli} (STEC) O103:H2 expresses enterohemolysin at high levels (34). 

\textbf{Clinical samples.} Fecal specimens from children infected with \textit{E. coli} O157:H7 were obtained from the Pacific Northwest. The Institutional Review Boards of the Children's Hospital and Regional Medical Center, Seattle, Wash., approved the use of these specimens, which were frozen immediately after collection and stored at −70°C until use.

Six conventional Holstein calves were housed in isolation units and pre-screened for health status and freedom from fecal STEC/enterohemorrhagic \textit{E. coli}. Half of the calves were obtained at 1 day of age, screened during week 1, inoculated on day 8, monitored for fecal shedding for 7 days, and euthanized and necropsied at 14 to 16 days of age. The remaining calves were obtained at 6 weeks of age, screened for 1 week, challenged at 7 weeks of age, monitored for fecal shedding for 7 days, and euthanized and necropsied between 54 and 58 days of age. Calves were orally challenged with 106 to 108 CFU of \textit{E. coli} O157:H7 strain 86-24Δ\textit{rfr} and monitored for 6 to 8 days for appetite, demeanor, diarrhea, and Na+ fecal shedding. At necropsy, approximately 50 g of fecal sample from the rectum was mixed in a stomacher bag, aliquoted, and frozen. The Washington State University Institutional Animal Care and Use Committee approved this research.

\textbf{Positive controls.} To create stool with known amounts of \textit{E. coli} O157:H7, bacteria were grown in LB broth to an optical density at 600 nm of 0.6 and 106 CFU were added per gram of stool donated by a healthy volunteer. To examine the sensitivity of the assay, stool was spiked with broth-grown \textit{E. coli} O157:H7 diluted in phosphate-buffered saline.

\textbf{RNA extraction from stool.} RNA was extracted using a modification of the silica-binding method (2, 4). Buffers L6, L11, L10, and L2 and silica were prepared as described previously (2, 4). Guanidine isothiocyanate (GITC)-containing buffers were stored in the dark and used within 3 weeks after preparation. The silica pH was adjusted to exactly 2.0 using 32% HCl. Approximately 0.2 g stool was mixed with 5 ml L6 containing 0.2 \mu g polyvinylpyrrolidone (PVP-40). For watery human samples and all bovine samples, the amount of stool was increased to 0.4 g. The mixture was vortexed thoroughly and centrifuged for 5 min at 4,300 \times g and 4°C. The supernatant was transferred to fresh tubes containing 2.5 ml GITC-phenol (7.5 M GITC, 0.5% sodium dodecyl sulfate, 1 mM EDTA, 50 mM sodium acetate [NaOAc] [pH 4.0], 50% \textit{H}2 \textit{O}3-saturated phenol) and 2.5 ml chloroform. The solution was vortexed and centrifuged (5 min, 4,300 \times g, 4°C). The supernatant was transferred to a fresh tube containing 10 ml ethanol (EtOH) and −20°C, and centrifuged (20 min, 4,300 \times g, 4°C). The precipitated nucleic acids were vacuum dried, resuspended in 3 ml L11, and split into 1-ml aliquots in microcentrifuge tubes, each containing 300 \mu l silica (pH 2.0) to bind DNA. The tubes were vortexed thoroughly, shaken (10 min, 4°C), and centrifuged (2 min, 2,000 \times g), and the
RNA-containing supernatants were transferred to a tube containing 700 μl L10 and 200 μl silica (pH 2.0) to bind RNA. Again, the tubes were vortexed thoroughly, shaken, and centrifuged under the same conditions, and the supernatants were discarded. The RNA-containing pellets were washed twice with 1 ml 70% EtOH, dried, and resuspended in a 1:1 solution of formamide and H2O.

DNA was eliminated using Ambion’s (Austin, TX) “DNA-free” DNase. Samples were treated twice following the recommendations of the manufacturer, using 1 unit of DNase per microgram of nucleic acid. RNA integrity after the DNase treatment was confirmed by visualizing rRNA after electrophoretic separation.

Primer and probes. Primers and probes were designed using Primer Express 2.0 (PE Applied Biosystems) and fluorescently labeled with 6-carboxyfluorescin (FAM) at the 5’ end and minor groove binder/nonfluorescent quencher at the 3’ end. Primers and probes were tested using positive control (spiked) stools (described above). Real time RT-PCR was also performed on normal stool without added bacteria.

Real-time RT-PCR. Real-time RT-PCR was performed on 50 ng fecal RNA by using the Invitrogen SuperScript III Platinum one-step quantitative RT-PCR system. TaqMan probes (described above) were used so that the reaction contained two levels of specificity: (i) the annealing of specific primers and (ii) hybridization of the probe. For each gene, amounts of primer, probe, and MgSO4 were optimized. These were used at the concentrations detailed in Table 2. All reactions using clinical samples were performed in triplicate using RNA from a single extraction. Reactions were run on a Rotor-Gene 2000 real-time cycler; program parameters were 55°C for 25 min, 95°C for 2 min, and 45 cycles of 95°C for 15 s and 60°C for 30 s. To confirm that RNA was free of DNA, an additional reaction was included that was identical to the RT-PCR but substituted platinum Taq for the RT enzyme mix provided in the kit. If a clinical specimen yielded no amplicon for a particular gene, the reaction was repeated. If only two of the three reactions yielded a product, these two were included in the analysis.

Standard curves. RNA was extracted from bacteria grown with shaking at 37°C to logarithmic phase (12). For each gene, real-time RT-PCR was performed on 10, 5, 1, 0.5, and 0.1 ng of RNA. Conditions were identical to those used for the clinical samples. A standard curve was generated by plotting log 10 ng RNA against the Ct value on the Rotor-Gene 2000 real-time cycler. The slope of the best-fit line was used to determine relative amounts for each gene for the clinical samples.

Table 2, Optimized conditions for amplification of each gene

<table>
<thead>
<tr>
<th>Gene</th>
<th>Probe (nM)</th>
<th>Primer (nM)</th>
<th>MgSO4 (mM)</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>eae</td>
<td>300</td>
<td>600</td>
<td>5</td>
<td>10^6</td>
</tr>
<tr>
<td>espA</td>
<td>300</td>
<td>400</td>
<td>5</td>
<td>10^6</td>
</tr>
<tr>
<td>espA</td>
<td>300</td>
<td>400</td>
<td>5</td>
<td>10^6</td>
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<tr>
<td>gnd</td>
<td>300</td>
<td>500</td>
<td>5</td>
<td>10^5</td>
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<tr>
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<td>300</td>
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<td>5</td>
<td>10^5</td>
</tr>
<tr>
<td>rfe</td>
<td>400</td>
<td>400</td>
<td>6</td>
<td>10^5</td>
</tr>
<tr>
<td>stx2</td>
<td>300</td>
<td>300</td>
<td>6</td>
<td>10^5</td>
</tr>
</tbody>
</table>

* CFU E. coli O157:H7/g of positive control stool containing smallest amount of E. coli O157:H7 detectable by this primer set.
RESULTS

Selection of genes for study. To determine if virulence genes are expressed differently when *E. coli* O157:H7 is excreted from humans compared to cattle, we selected several known or candidate virulence loci for expression analysis. These included LEE pathogenicity island genes *eae* and *espA*, as well as the gene encoding Shiga toxin 2 (*stx*). *stx* was selected because, unlike *stx*1 and other Shiga toxin variant genes, it is present in nearly all North American isolates (26, 39). We also included genes for which a role in human infection is uncertain: *rfe*E, which is involved in the synthesis of the O antigen of lipopolysaccharide (LPS), and *ehxA*, which encodes enterohemolysin. Finally, we included *iha*, which encodes Iha, an adherence-confering molecule that is a virulence factor in uropathogenic *E. coli* (16, 38). Levels of expression of these genes were related to that of a constitutively expressed housekeeping gene, *gnd*. *gnd* was selected as a reference locus because it is unusually polymorphic among *E. coli* housekeeping genes (25), enabling the specific analysis of expression of the O157:H7 gene against a background of commensal *E. coli*. Moreover, it differs from the *gnd* genes of related *E. coli* O55:H7 and *E. coli* with the O157 *rfe* region, which are only distantly related to *E. coli* O157:H7 and are not pathogens. Thus, *gnd*O157:H7 provides a target that is theoretically quite specific for the identification of pathogenic *E. coli* O157:H7.

RNA extraction from fecal samples. We developed an extraction method to isolate sufficiently pure RNA, free of RNases and inhibitors of enzymatic reactions. First, we employed a silica-binding method (2, 4) to isolate intact RNA as determined by separation on a 0.8% agarose gel (data not shown). However, we were unable to amplify fecal RNA obtained by this method, and we could not amplify RNA from broth-grown bacteria mixed 1:1 with fecal RNA extracted using this method. We suspected that inhibition of amplification reactions was at least in part the result of polyphenolics, which inhibit PCR (19). Polyphenolics are found in the leaves, bark, and fruit of most plants and reportedly copurify with nucleic acids during extraction from plant material and sludge (23, 37). PVP binds polyphenolics, and adding PVP-40 reduces inhibition of amplification by polyphenolics when included in an RNA extraction (15, 36, 37). Therefore, additional steps to optimize the RNA extraction protocol included adding PVP-40 in the lysis buffer, and the resulting procedure (see Materials and Methods) enabled the isolation of RNA suitable for RT-PCR from control (uninfected) human stool samples to which O157:H7 was added (data not shown).

Selection and optimization of primers and probes. Primers and TaqMan probes designed for real-time RT-PCR are shown in Table 1. Optimum concentrations of primer, probe, and MgSO4 were determined (Table 2) using positive control stools (described in Materials and Methods). For each gene, an increase in fluorescence during real-time RT-PCR was observed for RNA from human stool spiked with *E. coli* O157:H7 but not for RNA from unspiked stool containing commensal *E. coli* (data not shown). Furthermore, gene expression was not detected in RNA from a bovine fecal sample taken before infection (data not shown), nor was it detected in bovine samples with low numbers of *E. coli* O157:H7 (see below). Thus, the primers and probes are specific for *E. coli* O157:H7 and do not amplify codefected flora.

The sensitivity of the assay was determined by performing real-time RT-PCR on control stool spiked with serial dilutions of broth-grown *E. coli* O157:H7, ORN172(pIHA) (for *iha*), or STEC O103:H2 (for *ehxA*). ORN172(pIHA) and STEC O103:H2 highly express *iha* and *ehxA*, respectively, and were used because LB-grown O157:H7 expressed these genes at very low levels. The lowest dilution for which an increase in fluorescence was observed for each gene is listed in Table 2.

Analysis of human and bovine specimens. RNA was extracted from eight human and four bovine specimens. Six bovine specimens were available, but we could detect *E. coli* O157:H7 gene expression in only four. The remaining two specimens contained <105 CFU *E. coli* O157:H7/g. Each gene was amplified from each RNA preparation in triplicate. For the majority of the >80 reactions performed in triplicate, the C_T values within the triplicates varied by <10%. For four reactions, the C_T values of the triplicates varied by <35%. These four were cases in which the C_T value was >30, i.e., near the limit of detection. The relative amounts of RNA were determined from the experimental C_T values by reference to the standard curves.

Average relative amounts of mRNA for each gene were then normalized to the average relative amount of *gnd* mRNA of the same specimen. The resulting ratios were compared between human and bovine specimens by using the two-tailed Mann-Whitney test independently for each gene. For calf no. 3, in which expression of only some genes was detected, the sample was excluded from analysis for the genes whose expression was not detected. We elected to exclude these samples rather than assign an arbitrary low number because our statistical analysis used a nonparametric method that requires that the data be rank ordered. Assigning an artificial value had the potential to denote that data point with an incorrect rank and might have invalidated the results. Table 3 indicates the ratios of expression relative to *gnd*.

*iha* and *espA* exhibited statistically significant differences in expression between human and bovine hosts (Fig. 1). In both cases, the genes were more highly expressed in cattle feces. In contrast, *ehxA* (Fig. 2) (*P = 0.073*) and *rfe*E (*P = 0.11*) appeared to be more highly expressed in human stool, although these results failed to achieve statistical significance.

DISCUSSION

In addition to providing insight into host-specific virulence factor expression, we believe this study to be the first description of quantitative determination of specific bacterial mRNA levels in feces containing commensal flora. Preparation of RNA from cholera patient stools has previously been described (20, 22); however, these analytes were described as having a rice-water appearance characteristic of *Vibrio cholerae* stool, and microscopically, they contained few nonvibrios. Those authors did not mention any problems with inhibition and were able to extract RNA by using Trizol reagent, a phenol-chloroform based method. This suggests that cholera pa-
tient stools are relatively pure cultures of V. cholerae that possess few inhibitors. In contrast, our specimens were rarely aqueous, contained abundant commensal E. coli and other bacterial flora, and sometimes also contained blood or plant material which can inhibit PCR. We therefore believe that our RNA extraction technique can be applied to study gene expression of other bacteria that reside in the microbially complex milieu of the vertebrate intestine.

Because our specimens contained variable numbers of E. coli O157:H7, it was necessary to normalize virulence gene expression to an O157-specific control gene. gnd encodes the third enzyme of the pentose-phosphate pathway and is adjacent to the rfb cluster on the chromosome. Selective pressure for O-antigen diversity has led to a high mobility rate for the rfb region, and this recombination has also involved the neighboring gene gnd, which cotransfers with rfb (25, 40), generating variation in gnd. Therefore, though it is a housekeeping gene, it was necessary to normalize virulence gene expression to an O157-specific control gene.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Type</th>
<th>Patient outcome</th>
<th>Specimen status</th>
<th>CFU O157:H7/g</th>
<th>Ratio of transcript to that of gnd</th>
<th>eae</th>
<th>espA</th>
<th>ehxA</th>
<th>gnd</th>
<th>iha</th>
<th>rfbE</th>
<th>stx1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bovine</td>
<td>Normal</td>
<td>Normal</td>
<td>4.9 × 10^5</td>
<td>18</td>
<td>0.09</td>
<td>0.048</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Bovine</td>
<td>Normal</td>
<td>Normal</td>
<td>3.5 × 10^3</td>
<td>11</td>
<td>0.57</td>
<td>0.024</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Bovine</td>
<td>Normal</td>
<td>Normal</td>
<td>1.5 × 10^4</td>
<td>0.27</td>
<td>1.8</td>
<td>0.026</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The relative amount of each transcript was determined using standard curves, following which transcripts of the genes of interest were normalized to gnd.

All bovine samples were from calves obtained at 1 day of age except no. 7, which was obtained at 6 weeks of age.

Refers to ultimate outcome.

Refers to patient status at time sample was taken.

FIG. 1. Genes differentially expressed in human and bovine hosts. iha (A) or espA (B) expression normalized to gnd expression is shown with specimens grouped by source. The bars represent the means for human and bovine specimens (P < 0.05).

FIG. 2. ehxA exhibits a trend towards differential expression. ehxA expression normalized to gnd expression is shown with specimens grouped by source. The bars represent the means for human and bovine specimens (P = 0.073).
gnd is sufficiently polymorphic that we could design primers and probes specific for gnd of E. coli O157:H7. gnd mRNA abundance is regulated by the growth rate and fluctuates by 2.5-fold when grown on acetate versus glucose (29). This regulation is the result of growth rate rather than carbon source (45), and further regulation of 6-phosphogluconate dehydrogenase levels is achieved by posttranscriptional regulation via blocking of translation initiation (6). rRNA is often used as a constitutively expressed control, and its synthesis is also regulated according to growth rate (reviewed in reference 28). Therefore, gnd provides a comparable, O157-specific control for our specimens. It might also be a useful target for identifying E. coli O157:H7 in other microbiologically complex substances such as food or environmental samples.

In our samples, gnd expression roughly correlated with CFU/g of E. coli O157:H7, especially for the bovine samples (see supplementary Table 1 at http://faculty.washington.edu/moseley/rashidsup.pdf). For human fecal samples with a solid consistency we detected lower abundances of all genes, including gnd, than in human fecal samples with a liquid consistency. We speculate that this is the result of additional inhibitors from food being present in solid fecal samples, thus reducing detection of all messages. In support of this, samples B and C both contain approximately 10^8 CFU/g, but sample B is of solid consistency and C is of watery consistency (Table 3; see supplementary Table 1 at http://faculty.washington.edu/moseley/rashidsup.pdf). Supplementary Table 1 shows the raw data for all samples, and values for all genes are lower in the solid sample B. This suggests that inhibitors present in this and other solid samples affect all genes equally and further illustrates the need to normalize data internally prior to comparing across samples. In human samples, we observed the highest levels of gnd mRNA in the samples with the highest CFU per gram, which were of a liquid consistency. We did not detect gnd mRNA in fecal samples from a healthy human or a calf prior to infection, nor were we able to detect gnd in specimens from two calves with low CFU per gram. Thus, we conclude that detection of the O157:H7 gnd allele message by our primers specifies the presence of E. coli O157:H7.

We were able to detect gene expression in bovine and human clinical specimens at concentrations lower than those found to be the limit of detection in positive control stool (Table 2). We believe that this reflects a combination of differences in the inhibitors present in these specimens and differences in gene expression between broth-grown and feces-grown bacteria.

We found iha and espA to be more highly expressed in cattle than in humans. Iha, encoded by iha, is an adherence factor found among several pathotypes of E. coli (38, 42). espA is located in the LEE pathogenicity island, and EspA is important in forming a filament that bridges the bacterium and host cell and may be involved in protein translocation (17). Both Iha and EspA might play a role during colonization of the bovine intestine. In fact, EspA has been shown to be a colonization factor of STEC O26:H− during bovine colonization (43), and the LEE pathogenicity island was demonstrated to be important for bovine colonization of O157:H7 (10). Our data suggest that Iha might also act as a colonization factor in cattle. Host species specificity of colonization factors is well known. For example, different virulence factors of Salmonella enterica serovar Typhimurium are required for colonization of cattle compared to chickens (24). Similarly, Iha may play a more important role in bovine colonization than in human diarrheal disease. Such a role might allow Iha-expressing STEC to persist in their animal reservoirs prior to transmission to humans.

Another possible explanation for increased detection of iha and espA in cattle could be the presence of non-O157:H7 E. coli that contains these genes. However, in two specimens containing few O157:H7 CFU per gram of stool, we were unable to amplify any of the genes of interest, including iha and espA, and in a third we were unable to amplify espA. Additionally, we did not observe expression of any of these loci in a fecal sample from calf no. 7 prior to infection with E. coli O157:H7. This argues against the possibility that detection of these genes was the result of non-O157:H7 E. coli. Increased expression of iha and espA in O157:H7 remains the simplest and most likely explanation for detection of those genes in the bovine specimens.

Additional genes analyzed demonstrated trends towards higher expression in one species of host versus the other. We expect that this may have reached statistical significance had more specimens been available for analysis. Consistent with higher expression of LEE pathogenicity island gene espA in calves, eae also demonstrated a trend towards higher expression in calves. rfbE demonstrated a trend towards higher expression in the human, as did ehxA. rfbE, also called per, is necessary for expression of the O157 antigen on LPS (3). It is unclear why the bacterium would benefit from increased O-antigen expression in the human host compared to the bovine host. Perhaps the LPS provides a protective benefit to the bacterium. Although enterohemolysin has been demonstrated to have pore-forming activity (35), a defined role for this toxin during pathogenesis has been unclear. Our data support the possibility that enterohemolysin plays a role during human pathogenesis by E. coli O157:H7.

Iha is repressed by iron (R. A. Rashid, P. I. Tarr, and S. L. Moseley, submitted for publication). Our observation that iha is more highly expressed in cattle could indicate that the bovine host is more iron limiting than the human host. However, enterohemolysin expression is increased when cells are grown in iron-restricting medium (7), and ehxA showed a trend towards higher expression in specimens of human origin. This suggests that iron levels alone are unlikely to account for differences in expression of these genes.

Interestingly, not all genes demonstrated a trend towards host-specific expression: stx2 was not apparently differentially expressed. This observation could be due to a slight difference in expression that was undetected among the few specimens analyzed. Alternatively, the possibility exists that stx2 is equally expressed in humans and bovines. Indeed, stx2 is a late gene product of the temperate bacteriophage 933W (32). It has previously been noted that cattle may lack vascular Shiga toxin receptors (33) and that some Shiga toxins are activated by a compound present in mucus (18, 21). In conjunction with our data, these studies suggest the possibility that Stx-mediated pathogenesis may in part be regulated at the host level via receptors, activation of toxin, and possibly other factors.

We excluded from analysis those samples for which we did not detect expression, rather than assigning an arbitrary number. For calf no. 3, gnd levels were high. If espA is truly ex-
pressed below the limit of detection, then it might be valid to assign a low value for the espA ratio. If espA expression from this animal is assigned the lowest rank, statistical significance of the difference between espA expression in humans and cattle is lost. However, we do not know that our inability to detect espA in this sample is the result of low gene expression. Other possibilities include the loss or mutation of the LEE pathogenicity island during the course of infection or unexplained technical problems with the assay of this specimen. For these reasons, we elected to include in the analysis only samples for which we were able to detect message.

We observed wide variation of expression for a given gene within a host species. We do not believe this reflects detection of gene expression of normal flora for reasons described above. However, we are unable to explain the variation by correlating increased gene expression with disease status of the donor. It may be that fecal samples represent gene expression from a variety of locations within the intestine, including both adherent and nonadherent bacteria, which may have different gene expression profiles. Variability of gene expression from sample to sample remains a limitation of these data, and assessment of biological significance must be approached with caution.

Another limitation of our data is that the transcriptome of E. coli O157:H7 in feces may differ from that in organisms adhering to the mucosal surface in the intestines. Several studies have demonstrated in vitro the influence of epithelial adherence on bacterial gene expression (11, 30). Analysis of expression levels of bacteria at this site during the course of human infection would require biopsy material that would be difficult to obtain in sufficient quantity for analysis. Therefore, examination of fecal bacteria seems a practical alternative.

In support of this method, Larocque et al. detected differential gene expression between early and late stages of infection with V. cholerae by measuring gene expression in vomitus and feces (20).

It has previously been observed that E. coli O157:H7 regulates virulence gene expression in a lineage-specific manner (9). Our data suggest that this organism additionally regulates virulence gene expression in a host-specific manner.

In conclusion, our data support the hypothesis that at least a subset of E. coli O157:H7 virulence gene expression alters according to the host species. Additionally, our study provides a method of bacterial RNA isolation from mixed-flora fecal specimens that contain inhibitors, which may prove useful in the study of other intestinal tract pathogens and of the human enteric transcriptome in various additional states.

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