A review of an emerging enteric pathogen: enteroaggregative *Escherichia coli*

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Enteroaggregative *Escherichia coli* (EAEC) is an increasingly recognized enteric pathogen. It is a cause of both acute and persistent diarrhoea among children, adults and HIV-infected persons, in both developing and developed countries. In challenge studies, EAEC has caused diarrhoeal illness with the ingestion of $10^{10}$ c.f.u. Outbreaks of diarrhoeal illness due to EAEC have been reported, and linked to the ingestion of contaminated food. Diarrhoeal illness due to EAEC is the result of a complex pathogen–host interaction. Some infections due to EAEC result in diarrhoeal illness and elicit an inflammatory response, whereas other infections do not result in a symptomatic infection. Many putative virulence genes and EAEC strains that produce biofilm have been identified; however, the clinical significance of these genes and of biofilm production has yet to be defined. A $-251$ AA single nucleotide polymorphism (SNP) in the interleukin (IL)-8 promoter region is reported to increase host susceptibility to EAEC diarrhoea. Ciprofloxacin and rifaximin continue to be an effective treatment in persons infected with EAEC. This review is intended to provide an updated review for healthcare workers on EAEC, an emerging enteric pathogen.

**General considerations**

Diarrhoeagenic *Escherichia coli* is categorized into the following six pathotypes: enteropathogenic *E. coli* (EPEC), enterotoxigenic *E. coli* (ETEC), enterohaemorrhagic *E. coli* (EHEC), enteroinvasive *E. coli* (EIEC), diffusely adherent *E. coli* (DAEC), and enteroaggregative *E. coli* (EAEC). Other diarrhoeagenic *E. coli* pathotypes have been proposed, such as cell detaching *E. coli* (CDEC); however, their significance remains uncertain (Abduch-Fabrega et al., 2002; Clarke, 2001). Each of the pathotypes has distinguishing characteristics related to epidemiology, pathogenesis, clinical manifestations and treatment. EAEC is the most recently identified and described diarrhoeagenic *E. coli*. This bacterium was described in 1987, and identified in a child from Chile with persistent diarrhoea (Nataro, 2005).

EAEC has caused large diarrhoeal outbreaks in Europe, the UK, Switzerland and Japan. EAEC is also a common bacterial cause of diarrhoea among travellers to developing countries, and among children and HIV-infected persons residing in developing and developed regions of the world (Ruttler et al., 2002; Nataro et al., 2006). The virulence of EAEC strain 042 has been established in volunteers, who develop diarrhoea following an experimental challenge with an inoculum of $10^{10}$ c.f.u. (Nataro et al., 1995). A high inoculum required for disease development suggests a food or water vehicle as the likely mode of disease transmission for EAEC strains. A study of Mexican tabletop sauces identified 44% of sauces from Guadalajara, Mexico, to contain viable EAEC, compared to 0% of sauces in restaurants in Houston, TX (Adachi et al., 2002b).

EAEC is increasingly recognized as an emerging enteric pathogen. EAEC is a cause of persistent diarrhoea and malnutrition in children and HIV-infected persons living in developed countries, is the second most common cause of travellers’ diarrhoea (ETEC is the most common cause), and...
is a common cause of acute diarrhoeal illness in children and adults (4-5%) presenting to emergency departments and inpatient units in the USA (Cohen et al., 2005; Nataro et al., 2006). EAEC is also considered a potential bioterrorism agent (National Institutes of Health category B) (Huang & DuPont, 2004; Huang et al., 2004b). The objective of this review is to provide an update on this increasingly recognized emerging enteric pathogen.

**Epidemiology**

Numerous epidemiological studies of EAEC have been conducted. In a meta-analysis of published studies, EAEC was a cause of acute diarrhoeal illness in a median of 15% of children living in developing countries and 4% of children living in industrialized countries (Huang et al., 2006). These and other studies have examined the role of EAEC as a cause of diarrhoeal illness among other populations, in different regions of the world (Sanders et al., 2004; Sarantuya et al., 2004; Cohen et al., 2005). The populations best studied include children, adults and HIV-infected persons, living in developing and developed regions, and international travellers to developing countries. Many of these epidemiological studies conflict with regard to the pathogenicity of EAEC strains (Vernacchio et al., 2006), and many of these studies were not able to determine the importance of EAEC as a cause of diarrhoeal illness.

The data that support the virulence of EAEC come from a volunteer challenge study of EAEC prototype strain 042; outbreaks reported in Europe, the UK, Switzerland and Japan; large case-series and cohort studies of children, adults and HIV-infected persons living in developing and developed countries; and cases among international travellers to developing countries. In a volunteer challenge study, four groups of five volunteers were fed with one of four EAEC strains (042, 17-2, 34b and JM 221), each at a dose of 10^{10} c.f.u. (Nataro et al., 1995). Strain 042 caused diarrhoea in one group (three of five adults), whereas the other three strains failed to cause diarrhoea. These results support case-control and cohort-study findings of heterogeneity of EAEC in virulence. Four outbreaks of gastroenteritis due to EAEC occurred in the UK in 1994, occurring at different locations and at different times, and involving 19, 10, 51 and 53 persons, respectively. These illnesses were characterized by vomiting, diarrhoea and low-grade fever (Smith et al., 1997). In 1993, a massive outbreak of diarrhoea due to EAEC serotype O:H10 occurred in Japan. A total of 2697 children from 16 schools developed symptoms of abdominal pain, nausea and diarrhoea after presumably consuming contaminated school lunches (Itoh et al., 1997).

Several large population-based case-series of persons infected with EAEC have been described (Zamboni et al., 2004; Dulguer et al., 2003; Kang et al., 1995; Bhatnagar et al., 1993; Wilson et al., 2001; Knutton et al., 2001; Huppertz et al., 1997; Svenungsson et al., 2000). Table 1 shows pooled odds ratios (ORs) and confidence intervals (CIs) from a meta-analysis of epidemiologic studies of EAEC infections, identified by the HEp-2 cell-adherence assay, by population and region of the world (Huang et al., 2006). The OR represents the ratio of patients with diarrhoea from whom EAEC was isolated compared with those with asymptomatic EAEC infection. From the studies, EAEC was associated with acute diarrhoeal illness among children residing in developing and industrialized regions, HIV-infected adults residing in developing regions, adults residing in developing regions, and international travellers to developing regions. Limited studies have examined the role of EAEC in acute diarrhoeal illness among HIV-infected adults and non-HIV-infected adults residing in industrialized regions. Additional studies that are able to examine the role of EAEC in acute diarrhoea are needed.

It is likely that outbreaks of diarrhoea and diarrhoeal illness due to EAEC are underdiagnosed. Underdiagnosis of EAEC occurs because many public health and healthcare workers are not familiar with EAEC as a possible cause of diarrhoeal illness, and/or because limited research facilities with trained laboratory technicians are available to regularly perform assays to identify EAEC.

Like ETEC, EAEC is transmitted by the faecal–oral route. Risk factors for EAEC include travel to developing countries, ingestion of contaminated food and water, poor hygiene, host susceptibility, and possibly immunosuppression (HIV infection) (Huang & DuPont, 2004; Huang et al., 2004b).

**Table 1.** Epidemiology of EAEC infection among different populations living in different geographic areas of the world (Huang et al., 2006)

<table>
<thead>
<tr>
<th>Population studied</th>
<th>Pooled OR</th>
<th>95% CI</th>
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<tbody>
<tr>
<td>Children residing in developing countries (n=22)</td>
<td>1.58</td>
<td>1.36–1.83</td>
</tr>
<tr>
<td>Children residing in industrialized nations (n=9)</td>
<td>1.23</td>
<td>1.03–1.48</td>
</tr>
<tr>
<td>HIV-infected adults residing in developing regions (n=3)</td>
<td>6.43</td>
<td>2.91–14.16</td>
</tr>
<tr>
<td>HIV-infected adults residing in industrialized regions (n=2)</td>
<td>1.04</td>
<td>0.64–1.69</td>
</tr>
<tr>
<td>Adults residing in developing regions (n=2)</td>
<td>7.15</td>
<td>1.96–26.04</td>
</tr>
<tr>
<td>International travellers to developing regions (n=1)</td>
<td>6.72</td>
<td>2.62–17.20</td>
</tr>
</tbody>
</table>
Although EAEC has been identified as a cause of acute and chronic diarrhoea, it is unclear if HIV-infected persons are more likely to develop symptomatic EAEC infection in comparison to non-HIV-infected persons. It is also uncertain if EAEC represents an opportunistic infection (Gassama-Sow et al., 2004).

**Pathogenesis**

The pathogenesis of EAEC is complex, and EAEC strains are very heterogeneous (Elias et al., 2002). Human and animal studies indicate that EAEC is able to bind to jejunal, ileal and colonic epithelium. Electron microscopy of infected small- and large-intestinal mucosa, from children between 3 and 190 months, cultured with several different EAEC strains, reveals bacteria in a thick mucus layer above the intact enterocyte brush border (Hicks et al., 1996). In the colon, EAEC elicits inflammatory mediators and produces cytotoxic effects such as microvillus vesiculation, enlarged crypt openings, and increased epithelial cell extrusion (Harrington et al., 2005). Numerous putative virulence factors, a yersiniabactin system, a complex carbohydrate-specific lectin (Basu et al., 2004), enterotoxins and cytotoxins have been identified, but the clinical implication of these factors remains unclear (Table 2) (Jenkins et al., 2005; Jiang et al., 2002; Moon et al., 2005; Hu et al., 2005). The best-studied virulence factor is AggR, the master regulator of EAEC virulence, which controls expression of adherence factors, a dispersin protein, and a large cluster of genes encoded on the EAEC chromosome (Nataro, 2005). EAEC pathogenesis involves three stages: (1) adherence to the intestinal mucosa by aggregative adherence fimbriae (AAF) and adherence factors; (2) production of mucus by bacteria and the host cell forming a biofilm on the surface of

### Table 2. Putative EAEC virulence genes and virulence factors

<table>
<thead>
<tr>
<th>Gene</th>
<th>Description</th>
<th>References</th>
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<tbody>
<tr>
<td><strong>Master regulator gene</strong></td>
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<tr>
<td><em>aggR</em></td>
<td>Master regulator of a package of EAEC plasmid virulence genes, including genes encoding aggregative adherence factors, fimbriae AAF/I and AAF/II, a dispersin protein, and a large cluster of genes inserted on a pathogenicity island at the PheU locus</td>
<td>Nataro (1994, 2005); Jenkins et al. (2005); Sheikh et al. (2002)</td>
</tr>
<tr>
<td><strong>Fimbriae</strong></td>
<td></td>
<td></td>
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<tr>
<td><em>aafA</em></td>
<td>Encodes AAF/II, which mediates adherence to colonic mucosa</td>
<td>Czeczulin et al. (1997)</td>
</tr>
<tr>
<td><em>agg3</em></td>
<td>Encodes AAF/III</td>
<td>Bernier et al. (2002)</td>
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<tr>
<td><strong>Enterotoxins</strong></td>
<td></td>
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<tr>
<td><em>astA</em></td>
<td>Encodes the enteroaggregative heat-stable toxin, which has physical and mechanistic similarities to <em>E. coli</em> STa enterotoxin</td>
<td>Menard &amp; Dubreuil (2002); Menard et al. (2004)</td>
</tr>
<tr>
<td><em>pet</em></td>
<td>A 108 kDa autotransporter protein that functions as a heat-labile enterotoxin and cytotoxin</td>
<td>Eslava et al. (1998); Navarro-Garcia et al. (1999)</td>
</tr>
<tr>
<td><strong>OMPs</strong></td>
<td></td>
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<tr>
<td><em>OMP</em></td>
<td>Provides adherence capabilities of EAEC and haemagglutination of erythrocytes</td>
<td>Suzart et al. (1999); Monteiro-Neto et al. (2003)</td>
</tr>
<tr>
<td><strong>Dispersin transporter</strong></td>
<td></td>
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<tr>
<td><em>aatA</em></td>
<td>Encodes an ABC protein responsible for transporting the dispersin protein out of the outer membrane of EAEC</td>
<td>Nishi et al. (2003); Iwashita et al. (2006)</td>
</tr>
<tr>
<td><strong>Secreted proteins</strong></td>
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<tr>
<td><em>aap</em></td>
<td>Encodes a 10 kDa secreted protein named dispersin, and is responsible for 'dispersing' EAEC across the intestinal mucosa. Dispersin was immunogenic in a human EAEC challenge.</td>
<td>Nataro et al. (1995); Sheikh et al. (2002)</td>
</tr>
<tr>
<td><em>pic</em></td>
<td>Encodes a 109 kDa serine protease autotransporter protein that catalyses gelatin degradation. The Pic protein has mucinase activity and is capable of causing haemagglutination of erythrocytes.</td>
<td>Henderson et al. (1999); Behrens et al. (2002)</td>
</tr>
<tr>
<td><strong>Yersiniabactin system</strong></td>
<td></td>
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<tr>
<td><em>irp2</em></td>
<td>Encodes an iron-uptake system mediated by the siderophore yersiniabactin that plays a role in iron transport and regulation</td>
<td>Schubert et al. (1998)</td>
</tr>
<tr>
<td><strong>Lectin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lectin</td>
<td>A complex carbohydrate that shows cross-reactivity to the binding subunit of cholera toxin, and induces morphological changes in HEp-2 cells and fluid accumulation in the rabbit ileal loop.</td>
<td>Basu et al. (2004)</td>
</tr>
</tbody>
</table>
The second stage of EAEC pathogenesis involves production of a mucus layer by the bacteria and the intestinal mucosa; and (3) release of toxins and elicitation of an inflammatory response, mucosal toxicity and intestinal secretion (Nataro, 2005; Huang et al., 2004a; Harrington et al., 2005).

EAEC adherence to the intestinal mucosa requires AAF and adherence factors (Moreira et al., 2003). Three AAF structural subunits encoded by aggA (AAF/I), aafA (AAF/II) and agg-3 (AAF/III) on the 60–65 MDa pAA plasmid have been described. aggA encodes AAF/I, and is responsible for the aggregative phenotype and human erythrocyte haemagglutination of some EAEC strains (Nataro et al., 1993). aafA encodes AAF/II, which allows EAEC to adhere to the intestinal mucosa (Czeczulin et al., 1997). Both aggA and aafA are regulated by the transcriptional activator AggR. AAF/III functions as an adhesin, and is encoded by agg-3, which has a sequence closely related to that of the agg and aaf operon of DAEC (Bernier et al., 2002). Other adherence factors have been described. Three membrane-associated proteins (MAPs), of 18, 20 and 58 kDa, are believed to play an important role in EAEC adherence to and haemagglutination of animal cells (Spencer et al., 1998). One study has characterized the outer-membrane protein (OMP) profiles of EAEC strains from children with diarrhoea from Sao Paulo, Brazil, and has observed a heterogeneity in OMP profiles, suggesting that EAEC strains are very heterogeneous (Monteiro-Neto et al., 2003).

AggR regulates the expression of a secreted low-molecular-weight protein known as dispersin (aap) (Sheikh et al., 2002). Aap lies immediately upstream of aggR in EAEC strain 042. Dispersin is a 10-2 kDa protein that has been identified in 80% of EAEC isolates from one laboratory (Sheikh et al., 2002). This protein is exported by an ATP-binding cassette (ABC) transporter complex which is encoded by a genetic locus on the EAEC virulence plasmid pAA2 (Nishi et al., 2002). This locus consists of a cluster of five genes (designated aat-PABCD), including homologues of an inner-membrane permease (AatP), an ABC protein (AatC) and an OMP TolC (AatA). AatA localizes to the outer membrane independently of its ABC partner. Dispersin appears to require the Aat complex for outer-membrane translocation, but not for secretion across the inner membrane. In a similar manner to the dispersin gene (aap), transcription of the aat cluster is dependent on AggR, a regulator of a package of virulence genes in EAEC (Jenkins et al., 2005). Dispersin is responsible for mediating dispersal of EAEC across the intestinal mucosa to allow for efficient adherence and aggregation. This protein neutralizes the negatively charged LPS of the EAEC surface, allowing the positively charged AAF to splay out from the bacterium. In a volunteer challenge study, dispersin has been shown to be highly immunogenic, suggesting that it is a potential vaccine candidate (Nataro et al., 1995). Undoubtedly, other potential AAF and adherence factors exist, and they are currently being investigated.

The third stage of EAEC pathogenesis involves release of EAEC toxins, and elicitation of an inflammatory response, mucosal toxicity and intestinal secretion. Numerous EAEC toxins have been described. Both animal and human studies show that EAEC toxins are destructive to the tips and sides of intestinal villi and enterocytes. Several toxins are part of this process. The three toxins best studied are plasmid-encoded toxin (Pet) (Navarro-Garcia et al., 2001), EAEC heat-stable enterotoxin (EAST1) (Menard & Dubreuil, 2002), and Shigella enterotoxin 1 (ShET1) (Behrens et al., 2002). Pet is a cytopathic serine protease autotransporter that functions as an enterotoxin and a cytotoxin (Dutta et al., 2002). Intracellular expression of Pet is accompanied by cleavage of spectrin within the cytoskeleton of intestinal microvilli. In vitro studies show that purified toxin induces cell elongation and rounding, followed by exfoliation of cells.

Animal and in vitro culture studies show that EAEC survives within the mucus layer, explaining why individuals infected with EAEC, especially children in developing countries with pre-existent malnutrition, may develop mucoid stools, malnutrition, and persistent colonization with prolonged diarrhoea. One study has identified biofilm production in 48 of 62 (77%) EAEC strains from Japanese children with diarrhoea, using a quantitative biofilm assay, suggesting that this assay may be a useful and convenient screening tool for EAEC (Wakimoto et al., 2004). Transposon mutagenesis studies suggest that biofilm production by EAEC strain 042 is dependent on two genes. Fis is a chromosomal gene encoding a DNA-binding protein involved in growth-phase-dependent regulation, and yafK encodes a secreted 28 kDa protein (Sheikh et al., 2001). Both genes are mediated by AAF and likely reflect its interaction with the intestinal mucosa. Molecular epidemiologic studies are ongoing to determine the clinical impact of infection with EAEC strains that produce biofilm, and to investigate the genetic markers that identify biofilm-producing EAEC.

The third stage of EAEC pathogenesis involves release of EAEC toxins, and elicitation of an inflammatory response, mucosal toxicity and intestinal secretion. Numerous EAEC toxins have been described. Both animal and human studies show that EAEC toxins are destructive to the tips and sides of intestinal villi and enterocytes. Several toxins are part of this process. The three toxins best studied are plasmid-encoded toxin (Pet) (Navarro-Garcia et al., 2001), EAEC heat-stable enterotoxin (EAST1) (Menard & Dubreuil, 2002), and Shigella enterotoxin 1 (ShET1) (Behrens et al., 2002). Pet is a cytopathic serine protease autotransporter that functions as an enterotoxin and a cytotoxin (Dutta et al., 2002). Intracellular expression of Pet is accompanied by cleavage of spectrin within the cytoskeleton of intestinal microvilli. In vitro studies show that purified toxin induces cell elongation and rounding, followed by exfoliation of cells.
from the substratum. These effects are accompanied by loss of actin stress fibres and electrophysiologic changes (Sui et al., 2003). EAST1 is encoded by astA and is a heat-stable protein similar to the heat-stable toxin of ETEC. EAST1 was originally detected in EAEC strains. However, EAST1 has subsequently been identified in ETEC, EHEC, EPEC and DAEC.

The host inflammatory response to EAEC infection is dependent on the host innate immune system and the EAEC strain. The role of putative virulence genes and clinical outcomes is unclear. EAEC carrying ‘virulence’ genes are not always associated with disease; however, virulence factors are associated with increased levels of faecal cytokines and inflammatory markers, such as interleukin (IL)-1ra, IL-1β, IL-8, interferon (IFN)-γ, lactoferrin, faecal leukocytes, and occult blood (Jiang et al., 2002; Huang et al., 2004b). IL-8 is an important pro-inflammatory chemokine involved in EAEC pathogenesis. IL-8 is responsible for recruiting neutrophils to the epithelial mucosa without mucosal injury, and facilitates intestinal fluid secretion (Kucharzik et al., 2005; Sansonetti et al., 1999; Madara et al., 1993). Travellers to Mexico who developed symptomatic illness due to EAEC infection excreted high concentrations of faecal IL-8 compared to travellers who did not develop diarrhoea due to EAEC infection (Jiang et al., 2003). In addition to IL-8, intestinal epithelial cells infected with EAEC 042, the prototype strain, have been shown to upregulate the following genes: IL-6, tumour necrosis factor (TNF)-α, growth-related gene product (GRO)-α, GRO-γ, intercellular adhesion molecule (ICAM)-1, granulocyte-macrophage colony-stimulating factor (GM-CSF) and IL-1z. These cellular responses are primarily mediated by flagellin (flhC), a major bacterial surface protein of EAEC (Harrington et al., 2005). Flagellin causes IL-8 release from several epithelial cell lines by binding to Toll-like receptor 5 (TLR5). TLR5 signals through P38 mitogen-activating protein kinase (MAPK) and nuclear factor kappa B (NF-kB) to induce transcription of pro-inflammatory cytokines from epithelial and monocyteic cells (Khan et al., 2004). MAPK is a member of a family of stress-related kinases that influences a diverse range of cellular functions, including host inflammatory responses to microbial products (Khan et al., 2004).

It is clear that multiple factors contribute to EAEC-induced inflammation, and further characterization of the nature of EAEC pro-inflammatory factors will greatly advance the understanding of this emerging pathogen.

### Clinical manifestations of EAEC infection

The clinical symptoms of EAEC infection vary from one study to another (Table 3). Although not all EAEC infections result in symptomatic illness (Adachi et al., 2002a), most studies suggest that EAEC infection results in gastrointestinal disease. The most commonly reported symptoms are watery diarrhoea with or without blood and mucus, abdominal pain, nausea, vomiting, and low-grade fever. EAEC can cause both an acute and a chronic (>14 days) diarrhoeal illness. Malnourished hosts, especially children living in developing countries, may be unable to repair mucosal damage and thus may become prone to persistent or chronic diarrhoea. The incubation period of EAEC diarrhoeal illness ranges from 8 to 18 h. The myriad variations of clinical symptoms of EAEC infection are due to factors such as host genetic susceptibility, host immune response, heterogeneity of virulence among EAEC strains, and the amount of bacteria ingested by the infected host.

### Host susceptibility

Clinical manifestations of EAEC diarrhoea vary from individual to individual, depending upon the genetic composition of the host (Jiang et al., 2003). The distribution of IL-8 genotypes in symptomatic and asymptomatic subjects infected with EAEC has been studied. Differences in the allele frequencies of T to A polymorphisms in the promoter region of IL-8 located −251 bp upstream of the transcription start site have been identified (Jiang et al., 2003). An AA (OR 208; 95% CI 28:5–1525:4) or AT (OR 14:3; 95% CI 1:98–105:7) genotype at the −251 position in the promoter region of IL-8 results in greater chances of developing symptomatic EAEC infection compared with those of the TT genotype (Jiang et al., 2003). An AA genotype is also associated with increased concentrations of faecal IL-8 than those of the AT and TT genotypes. Single nucleotide polymorphisms (SNPs) in regulatory and codon

### Table 3. Clinical manifestations of EAEC infection

<table>
<thead>
<tr>
<th>Clinical symptoms</th>
<th>Range</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>Watery diarrhoea</td>
<td>0–76%</td>
<td>Nataro (2005); Adachi et al. (2002a); Glandt et al. (1999); Infante et al. (2004); Kahali et al. (2004)</td>
</tr>
<tr>
<td>Abdominal pain/cramping</td>
<td>45–5%</td>
<td>Kahali et al. (2004)</td>
</tr>
<tr>
<td>Nausea ± vomiting</td>
<td>41–1–64.5%</td>
<td>Kahali et al. (2004); Pabst et al. (2003)</td>
</tr>
<tr>
<td>Fever (&gt;38.5°C)</td>
<td>18–19–8%</td>
<td>Kahali et al. (2004); Pabst et al. (2003)</td>
</tr>
<tr>
<td>Stool characteristics</td>
<td></td>
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</tr>
<tr>
<td>Diarrhoea with blood</td>
<td>3–3–31–1%</td>
<td>Regua-Mangia et al. (2004); Bouckenooghe et al. (2000)</td>
</tr>
<tr>
<td>Diarrhoea with mucus</td>
<td>4–1–55–2%</td>
<td>Regua-Mangia et al. (2004); Bouckenooghe et al. (2000)</td>
</tr>
<tr>
<td>Diarrhoea with faecal leukocytes</td>
<td>28–9%</td>
<td>Regua-Mangia et al. (2004); Bouckenooghe et al. (2000)</td>
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</table>
regions of other chemokines and cytokines are an area of active investigation. In addition to determining host susceptibility to EAEC infection, SNPs are important in studying the epidemiology, risk assessment and pathogenesis of EAEC. These factors may define populations that benefit from therapeutic interventions, such as prophylactic antibiotic therapy or vaccination.

**Diagnosis**

The gold standard for identifying EAEC is the HEp-2 cell-adherence assay (Nataro & Kaper, 1998). This assay identifies EAEC by its ‘stacked brick’ aggregating phenotype (Fig. 1). Variations in the assay have been described. A formalin-fixed HEp-2 cell-adherence assay is reported to be sensitive (98%) and specific (100%) compared to the traditional assay, while reducing the risk of contamination (Miqdady et al., 2002). It remains to be determined if this assay will improve the efficiency of EAEC identification and be routinely used in diagnostic laboratories. The HEp-2 cell-adherence assay is currently performed only in research settings, and is labour intensive (Huang et al., 2004b). A clump formation test has also been described to be useful in the identification of EAEC (Iwanaga et al., 2002).

Other diagnostic tools for identifying EAEC have been reported (Table 4) (Bouzari et al., 2005; Ruiz-Blazquez et al., 2005). A DNA probe from the pAa plasmid of EAEC is specific for EAEC strains, but has variable sensitivity (Scaletsky et al., 2002). A PCR, a multiplex PCR, and a real-time PCR assay to detect EAEC virulence genes and a plasmid region corresponding to the DNA probe, are also available (Amar et al., 2004). A problem with using DNA probes and PCR assays to identify EAEC is that EAEC strains are very heterogeneous, and this may account for the varying sensitivity of these techniques (Sarantuya et al., 2004).

**Treatment**

EAEC infections are usually self-limiting and responsive to oral rehydration therapy (Huang et al., 2004b). Antimicrobial therapy for travellers’ diarrhoea and paediatric diarrhoea should be based on an individual basis, and remains largely an empirical treatment (DuPont & Ericsson, 1993). Antimicrobial susceptibility patterns of EAEC strains vary by geographic region. Some studies have reported EAEC to have moderate- to high-level resistance to ampicillin, tetracycline, trimethoprim, sulfamethoxazole and chloramphenicol (Sobieszczanska et al., 2003). One study suggests that integrons that include the dfrA5, aadA1, drA13 and oxa5 cassette may be responsible for antibiotic resistance in EAEC (Gassama et al., 2004). In most regions of the world, EAEC strains are susceptible to fluoroquinolones, azithromycin, rifaximin, amoxicillin/clavulanic acid, and nalidixic acid (Glandt et al., 1999; Infante et al., 2004).

Two clinical trials have been conducted evaluating treatment of EAEC diarrhoea in travellers (Table 5). The first trial evaluated the clinical response of travellers with EAEC diarrhoea to ciprofloxacin (500 mg twice a day for 3 days) (Glandt et al., 1999), and the second trial evaluated the clinical response to rifaximin (200 and 400 mg twice a day for 3 days), a poorly absorbed antimicrobial agent (Infante et al., 2004). In the first trial, 29 of 64 (45%) US travellers to Jamaica and Mexico developed diarrhoea due to EAEC. Sixteen of the patients were treated with ciprofloxacin and 13 with placebo. The patients treated with ciprofloxacin had a significant reduction in the duration of post-treatment diarrhoea (35 versus 56 h), and a non-significant reduction in the mean number of unformed stools passed during the 72 h after enrolment compared to patients who received placebo (six episodes versus eight episodes). The second trial was multicentred, and included 43 of 137 (32%) US travellers to Guatemala, Kenya and Mexico who developed diarrhoea due to EAEC. Thirty of the patients were treated with rifaximin and 13 with placebo. The patients treated with rifaximin had a significant reduction in the duration of post-treatment diarrhoea compared to placebo (22 versus 72 h).

**Conclusion**

EAEC is an increasingly recognized cause of diarrhoea. It is a cause of acute and chronic diarrhoea among children, adults and HIV-infected persons. EAEC has been responsible for diarrhoea in a volunteer study and in numerous outbreaks and case-control studies from both the developing and the developed world. EAEC causes gastrointestinal disturbance by a complex host–pathogen

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**Table 4. Available diagnostic tools for the identification of EAEC**

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<tr>
<th>Diagnostic tool</th>
<th>Source</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formalin-fixed HEp-2 cell-adherence assay</td>
<td>Bacteria</td>
<td>94–98 %</td>
<td>100 %</td>
<td>Miqdady et al. (2002)</td>
</tr>
<tr>
<td>Real-time PCR (LightCycler assay)</td>
<td>Bacteria</td>
<td>100 %</td>
<td>100 %</td>
<td>Bischoff et al. (2005)</td>
</tr>
<tr>
<td>DNA probe (CVD432)</td>
<td>Bacteria</td>
<td>15–89 %</td>
<td>99 %</td>
<td>Bouzari et al. (2005); Scaletsky et al. (2002)</td>
</tr>
<tr>
<td>PCR (aggR, aap, aggA, aadA, astA)</td>
<td>Bacteria</td>
<td>86–94 %</td>
<td>78–100 %</td>
<td>Cerna et al. (2003); Ruiz-Blazquez et al. (2005); Ruttler et al. (2002); Tsai et al. (2003)</td>
</tr>
<tr>
<td>Multiplex PCR (CVD432)</td>
<td>Bacteria</td>
<td>100 %</td>
<td>100 %</td>
<td>Aranda et al. (2004); Nguyen et al. (2005)</td>
</tr>
<tr>
<td>Clump formation test</td>
<td>Bacteria</td>
<td>82–100 %</td>
<td>89–100 %</td>
<td>Iwanaga et al. (2002)</td>
</tr>
</tbody>
</table>
interaction that involves host genetic susceptibility, heterogeneity of virulence among EAEC strains, and the amount of bacteria ingested by the infected host. Although identification of EAEC is currently limited to research laboratories, new and more efficient ways of identifying EAEC are being developed to allow for standardized laboratory testing on a regular basis. EAEC infections are usually self-limiting, and should be managed on an individual basis. However, two clinical trials have shown that EAEC diarrhoea in travellers is responsive to ciprofloxacin and rifaximin therapy. This review describes the importance of EAEC as an enteric pathogen, updates the epidemiology, pathogenesis, diagnosis and treatment of EAEC, and highlights the importance of further study of EAEC to advance our understanding of this increasingly recognized emerging enteric pathogen.

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References


Amar, C. F., East, C., Maclure, E., McLauchlin, J., Jenkins, C., Duncanson, P. & Wareing, D. R. (2004). Identification of virulence among EAEC strains, and the amount of bacteria ingested by the infected host. Although identification of EAEC is currently limited to research laboratories, new and more efficient ways of identifying EAEC are being developed to allow for standardized laboratory testing on a regular basis. EAEC infections are usually self-limiting, and should be managed on an individual basis. However, two clinical trials have shown that EAEC diarrhoea in travellers is responsive to ciprofloxacin and rifaximin therapy. This review describes the importance of EAEC as an enteric pathogen, updates the epidemiology, pathogenesis, diagnosis and treatment of EAEC, and highlights the importance of further study of EAEC to advance our understanding of this increasingly recognized emerging enteric pathogen.

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