Prevalence and pathogenicity of Shiga toxin-producing *Escherichia coli* in beef cattle and their products

H. S. Hussein

J ANIM SCI 2007, 85:E63-E72.
doi: 10.2527/jas.2006-421 originally published online October 23, 2006

Prevalence and pathogenicity of Shiga toxin-producing *Escherichia coli* in beef cattle and their products[1,2]

H. S. Hussein[3]

Department of Animal Biotechnology, University of Nevada, Reno 89557

ABSTRACT: During the past 23 yr, a large number of human illness outbreaks have been traced worldwide to consumption of undercooked ground beef and other beef products contaminated with Shiga toxin-producing *Escherichia coli* (STEC). Although several routes exist for human infection with STEC, beef remains a main source. Thus, beef cattle are considered reservoirs of O157 and nonO157 STEC. Because of the global nature of the food supply, safety concerns with beef will continue, and the challenges facing the beef industry will increase at the production and processing levels. To be prepared to address these concerns and challenges, it is critical to assess the beef cattle role in human infection with STEC. Because most STEC outbreaks in the United States were traced to beef containing *E. coli* O157:H7, the epidemiological studies have focused on the prevalence of this serotype in beef and beef cattle. Worldwide, however, additional STEC serotypes (e.g., members of the O26, O91, O103, O111, O118, O145, and O166 serogroups) have been isolated from beef and caused human illnesses ranging from bloody diarrhea and hemorrhagic colitis to the life-threatening hemolytic uremic syndrome (HUS). To provide a global assessment of the STEC problem, published reports on beef and beef cattle in the past 3 decades were evaluated. The prevalence rates of *E. coli* O157 ranged from 0.1 to 54.2% in ground beef, from 0.1 to 4.4% in sausage, from 1.1 to 36.0% in various retail cuts, and from 0.01 to 43.4% in whole carcasses. The corresponding prevalence rates of nonO157 STEC were 2.4 to 30.0%, 17.0 to 49.2%, 11.4 to 49.6%, and 1.7 to 58.0%, respectively. Of the 162 STEC serotypes isolated from beef products, 43 were detected in HUS patients and 36 are known to cause other human illnesses. With regard to beef cattle, the prevalence rates of *E. coli* O157 ranged from 0.3 to 19.7% in feedlots and from 0.7 to 27.3% on pasture. The corresponding prevalence rates of nonO157 STEC were 4.6 to 55.9% and 4.7 to 44.8%, respectively. Of the 373 STEC serotypes isolated from cattle feces or hides, 65 were detected in HUS patients and 62 are known to cause other human illnesses. The results indicated the prevalence of a large number of pathogenic STEC in beef and beef cattle at high rates and emphasized the critical need for control measures to assure beef safety.

Key words: beef, beef cattle, *Escherichia coli*, foodborne pathogen, Shiga toxin

 J. Anim. Sci. 2007. 85(E. Suppl.):E63–E72
doi:10.2527/jas.2006-421

INTRODUCTION

The importance of beef safety increased since reporting the first 2 human illness outbreaks caused by consumption of ground beef contaminated with *Escherichia coli* O157:H7 (Riley et al., 1983). Because of tracing a large number of *E. coli* O157:H7 outbreaks to beef in the United States during the past 23 yr (CDC, 1993, 2003; Rodrigue et al., 1995), most US studies focused on this pathogen in beef cattle (Hancock et al., 1994; Galland et al., 2001; Barkocy-Gallagher et al., 2003) or their edible products (Doyle and Schoeni, 1987; Elder et al., 2000; Barkocy-Gallagher et al., 2003). Worldwide, other Shiga toxin-producing *E. coli* (**STEC**) serotypes were isolated from beef cattle (Beutin et al., 1997; Pradel et al., 2000; Leomil et al., 2003) or their products (Sekla et al., 1990; Leung et al., 2001; Khan et al., 2002) and caused human illnesses (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006).

In addition to beef (CDC, 1993; López et al., 1997; CDC, 2003), human infections were traced to vegetables (Cieslak et al., 1993), raw milk (Martin et al., 1986;

[1]Presented at the ADSA-ASAS Joint Annual Meeting, Food Safety Symposium: Ruminants as Reservoirs for Shiga Toxin-Producing *Escherichia coli,* Minneapolis, MN, July 2006.

[2]The author would like to acknowledge the support of the Integrated Research, Education, and Extension Competitive Grants Program—National Integrated Food Safety Initiative (grant No. 2001-51110-11463) of the USDA Cooperative State Research Education, and Extension Service.

[3]Corresponding author: hhussein@cabnr.unr.edu

Received June 29, 2006.
Accepted October 12, 2006.

Herriott et al., 1994; Lahti et al., 2002), dairy products (Morgan et al., 1993; Reid, 2001), and drinking water (Yatsuyanagi et al., 2002) containing STEC. Other infection routes included person to person (Reida et al., 1994) and animal to person (Synge et al., 1993; Crump et al., 2002). The infection caused human illnesses (Griffin and Tauxe, 1991; Paton and Paton, 2000) ranging from mild diarrhea to hemolytic uremic syndrome (**HUS**) that could lead to death (Pavia et al., 1990; CDC, 1993; Cowden, 1997). Because beef cattle are considered reservoirs for O157 (Hancock et al., 1994; Chapman et al., 2001; Al-Saigh et al., 2004) and nonO157 STEC (Schurman et al., 2000; Geue et al., 2002; Barkocy-Gallagher et al., 2003), safety concerns with beef, especially in the ground form, will continue to be a major challenge for the beef industry. This is critically important because recent evidence (Hussein and Bollinger, 2005a,b; Hussein and Sakuma, 2005) illustrated a large number of pathogenic STEC serotypes to derive from bovine origin. To be prepared to address current and future safety concerns and challenges, it is critical for the beef industry to develop strategies supporting beef safety. This review is intended to provide a global assessment of the beef cattle role in human infection with STEC.

HUMAN DISEASE OUTBREAKS FROM STEC OF BEEF CATTLE ORIGIN

In a large number of the reported outbreaks and sporadic cases of human illnesses, STEC infection was attributed to consumption of undercooked ground beef or other beef products (i.e., roast or smoked beef, sausage, steak, or tri-tip, and veal) contaminated with O157 (Orr et al., 1994; Cowden, 1997; CDC, 2003) or nonO157 (Caprioli et al., 1994; López et al., 1997; Henning et al., 1998) serotypes. The human illnesses included (Nataro and Kaper, 1998) mild diarrhea, abdominal pain, vomiting, bloody diarrhea, hemorrhagic colitis (**HC**), strokes, and HUS. The HC is characterized by bloody diarrhea, abdominal cramps, fever, and vomiting (Griffin and Tauxe, 1991). The HUS is characterized by thrombocytopenia, microangiopathic hemolytic anemia, and acute renal failure due to production of toxins that damage endothelial cells and trigger the clotting mechanism (Donnenberg, 2002). The HUS is more common in infants, children, the elderly, and those with compromised immune function (Paton and Paton, 2000). Although most HUS patients recover, some die and some may develop strokes (Griffin and Tauxe, 1991) or chronic renal failure (Remuzzi, 1987; Fitzpatrick et al., 1991; Siegler et al., 1991). Other symptoms of STEC infection include diabetes mellitus and necrotizing colitis (Paton and Paton, 2000).

Evaluation of published reports in the past 23 yr revealed 146 STEC outbreaks and sporadic cases of human illnesses to be traced to consumption of beef contaminated with various *E. coli* O157 strains (Bollinger, 2004). These strains belonged to *E. coli* O157:H7, O157:H$^-$ (a nonmotile isolate), and others that were not typed for the H antigen. Of these outbreaks and sporadic cases, 88% were traced to ground beef, 89% occurred in the United States, and 11% occurred in the United Kingdom (8), Canada (2), Germany (2), Japan (2), Argentina (1), and Central African Republic (1). The large number of outbreaks and cases in the United States could be explained by the high level of ground beef consumption at fast food restaurants and by availability of *E. coli* O157 diagnostic methods. Some of the outbreaks involved large numbers of affected people (ranging from 303 to 736) as shown in Canada (Orr et al., 1994), the United Kingdom (Cowden, 1997), and the United States (CDC, 1993, 2003). These outbreaks emphasized the role of beef as an important vehicle of *E. coli* O157 transmission (CDC, 1993; USDA-APHIS-VS, 1997; CDC, 2003).

A smaller number of outbreaks (6 total) of human illnesses was attributed to infections with nonO157 STEC strains from contaminated beef (Bollinger, 2004). These infections involved 8 STEC serogroups (O1, O2, O15, O25, O75, O86, O111, and O160) and 3 serotypes (O26:H11, O111:H7, and O111:H$^-$). These outbreaks were reported in Argentina, Australia, Germany, and Italy and were traced to consumption of undercooked ground beef or its sausage. Two of these outbreaks involved large numbers of affected people (161 and 433) as shown in Australia (CDC, 1995) and Argentina (López et al., 1997), respectively. The significance of nonO157 STEC infections through contaminated beef was illustrated in the incidence of HUS cases in 5 of the 6 reported outbreaks (Bollinger, 2004). In these outbreaks, most HUS patients were children or the elderly, reflecting the naivety of the immune system of young children and the declining immune function of the elderly (Paton and Paton, 2000). Although infection with *E. coli* O26:H11 did not lead to HUS in the outbreak reported (Werber et al., 2002), it is known to cause HUS (WHO, 1998; Anonymous, 2001; Blanco et al., 2003).

BEEF CATTLE AS RESERVOIRS FOR STEC

Although various STEC strains have been isolated from different animals (Beutin et al., 1993; 1995), they have been shown to be more prevalent in ruminants than in other animals (Beutin et al., 1993; Caprioli et al., 1993; Beutin et al., 1995). In addition, human illnesses due to STEC infection have been traced in most cases to cattle (Bielaszewska et al., 2000; Crump et al., 2002), their manure (Wilson et al., 1992; Cieslak et al., 1993; Lahti et al., 2002), or their edible products, especially beef (Riley et al., 1983; López et al., 1997; CDC, 2003). A wide distribution of STEC among various beef cattle categories was documented by isolation of different serotypes from bulls (Čižek et al., 1999), cows (Shinagawa et al., 2000; Gannon et al., 2002; Hussein et al., 2003), heifers (Schurman et al., 2000; Thran et al., 2001; Ezawa et al., 2004), steers (Schurman et al.,

2000; Gioffré et al., 2002; Smith et al., 2004), and calves (Gannon et al., 2002; Leomil et al., 2003; Cobbold et al., 2004). Additionally, STEC are commonly detected in cattle in feedlots (Hancock et al., 1997; LeJeune et al., 2004; Padola et al., 2004) and under grazing conditions (Gannon et al., 2002; Cobbold et al., 2004; Pearce et al., 2004).

BEEF CATTLE AS TRANSIENT CARRIERS OF STEC

Beef cattle have not been reported as long-term carriers of STEC. Besser et al. (1997) reported that the duration of detected excretion of *E. coli* O157:H7 by individual US cattle was shorter than 1 mo in 63% of the cattle tested. Similar results were also reported for Japanese cattle (Ohya and Ito, 1999). It is worth noting that the carriage of these pathogens was shown to fluctuate significantly over time in US feedlots (Hancock et al., 1997; Khaitsa et al., 2003; LeJeune et al., 2004). Testing feedlot cattle in 13 states during winter showed a decrease in prevalence rate from 4.6 to 1.3% by increasing the time on feed from 7 to 185 d (Hancock et al., 1997). In a North Dakota study, however, the prevalence rate rose during winter from 1.4% on arrival to 6.9% at 28 d on feed (Khaitsa et al., 2003). Testing cattle in 20 feedlot pens during spring also showed fluctuations in the prevalence rates (15, 28, 22, and 12%) at different times (7, 14, 28, and 42 d, respectively) on feed (LeJeune et al., 2004). Shedding of STEC by beef cattle has been shown to increase during the warm months, which is consistent with the timing of most human illness outbreaks (USDA-APHIS-VS, 1997). In the US, testing beef cattle over 1 yr revealed the highest (9%) and lowest (5%) prevalence rates for the fall and winter, respectively (Cobbold et al., 2004). Similar results were reported in Germany when 2 grazing beef herds were tested over 2 yr (Geue et al., 2002). In our laboratory (Thran et al., 2001), however, fecal testing of grazing beef heifers over 1 yr revealed the highest (15%) prevalence rate to occur in winter and the lowest (4%) to occur in the spring and fall. In another grazing study (Jenkins et al., 2002), the highest (22%) and lowest (6%) prevalence rates occurred in the summer and fall, respectively. Testing cattle at slaughter for *E. coli* O157 revealed the highest and lowest prevalence rates to occur in the warm and cold months, respectively, in Finland (Lahti et al., 2001) and the United Kingdom (Chapman et al., 2001; Paiba et al., 2002). In the United States, testing Midwestern cattle (Barkocy-Gallagher et al., 2003) at slaughter showed *E. coli* O157:H7 to be more prevalent in the summer than in winter (12.9 vs. 0.3%) and nonO157:H7 STEC to be more prevalent in the fall (27.1%) than in the summer or winter (14.0%). In France (Pradel et al., 2000), 58 STEC serotypes were prevalent at very high rates in the summer (85%) and spring (46%), and the cattle were transient in infection.

PREVALENCE OF STEC IN BEEF CATTLE

Hussein and Bollinger (2005a) reviewed published reports in the past 3 decades and summarized the prevalence of STEC in beef cattle feces and hides. In general, the prevalence rates of *E. coli* O157 ranged from 0.3 to 19.7% in feedlot cattle, from 0.7 to 27.3% in cattle on irrigated pasture, and from 0.9 to 6.9% in cattle grazing rangeland forages. These observations suggest a high potential for infection and reinfection of cattle with *E. coli* O157 during grazing of the dense vegetation on pasture. On the range, however, cattle travel in large and less-dense areas seeking edible vegetation. With regard to testing for *E. coli* O157 at slaughter, the prevalence rates ranged from 0.2 to 27.8%. Worldwide, the prevalence rates of nonO157 STEC ranged from 4.6 to 55.9% in feedlot cattle and from 4.7 to 44.8% in grazing cattle. With regard to testing for nonO157 STEC at slaughter, the prevalence rates ranged from 2.1 to 70.1%. These observations indicate that nonO157 STEC are prevalent in all beef production systems at rates as high as 70.1%. The ranges of prevalence rate, however, varied widely and could be explained by the significant impact of environmental factors, by management practices on promoting or decreasing STEC prevalence, or both.

Cattle hides have been identified as an important source of microbial contamination of carcasses (Ridell and Korkeala, 1993; Bell, 1997; McEvoy et al., 2000). It has been shown that O157:H7 and nonO157:H7 STEC can be easily transferred from cattle hides to the carcass (Barkocy-Gallagher et al., 2003). Because of the role that cattle hides can play in carcass contamination with STEC at slaughter, efforts (Bacon et al., 2000; Elder et al., 2000; Barkocy-Gallagher et al., 2003) have been devoted to evaluate its significance. Testing swab samples from cattle hides at 12 US beef processing plants in the fall revealed a 3.6% prevalence rate of *E. coli* O157:H7 (Bacon et al., 2000). A higher prevalence rate (10.7%) of *E. coli* O157 was reported when cattle hides were tested in the summer at 4 Midwestern beef processing plants (Elder et al., 2000). These different prevalence rates could be explained by sampling time (i.e., fall vs. summer). Because a large number of variables (e.g., management practices, diets fed, animal factors, and methods of STEC detection) can influence STEC prevalence, comparisons among studies should be carefully evaluated. Significant seasonal differences in the prevalence rates of O157:H7 and nonO157:H7 STEC were also found (Barkocy-Gallagher et al., 2003) preharvest (i.e., feces and hides) and postharvest (i.e., carcasses). In this study, testing fecal, hide, and carcass swab samples from cattle at 3 Midwestern beef processing plants over 1 yr (Barkocy-Gallagher et al., 2003) revealed the prevalence of O157:H7 and nonO157:H7 STEC at high rates. The prevalence rates for O157:H7 and nonO157:H7 STEC, however, varied among cattle hides (60.6 and 56.6%, respectively), feces (5.9 and 19.4%, respectively), and carcasses (26.7 and 58.0%,

respectively). With regard to cattle hides, prevalence of *E. coli* O157:H7 was highest in the spring, summer, and fall (averaging 71.5%) and lowest in winter (29.4%). Prevalence of nonO157:H7 STEC, however, was lowest in the winter, spring, and summer (averaging 49.2%) and highest in the fall (77.7%). In this study, no attempt was made to serotype the nonO157:H7 isolates.

The concentration at which STEC is shed in feces varies from animal to animal as demonstrated in a US study (Zhao et al., 1995), where a range from 10^2 to 10^5 cfu of *E. coli* O157:H7/g of wet feces was observed. It is important to note that quantitative fecal shedding of STEC is considered (Omisakin et al., 2003; Ogden et al., 2004) a more important factor than prevalence in influencing the risk of human exposure and infection with these foodborne pathogens. For example, prevalence of *E. coli* O157 in Scottish beef cattle at slaughter was found (Ogden et al., 2004) to be greater ($P < 0.05$) during the cooler months (11.2%) than during the warmer months (7.5%). This is the reverse of the known seasonality of human infections with STEC (WHO, 1998). Ogden et al. (2004) reported their high shedding beef cattle (i.e., excreting > 10^4 cfu/g of wet feces) to shed greater concentrations of *E. coli* O157 in the warmer months, which may explain increased human infections at that time. Interestingly, the high shedding cattle (9% of the cattle tested) excreted the largest amount of *E. coli* O157 (96%) produced.

PREVALENCE OF STEC IN BEEF PRODUCTS

Contamination of beef carcasses with STEC usually occurs during removal of the hide or the gastrointestinal tract (Elder et al., 2000; McEvoy et al., 2003). The site and extent of carcass contamination subsequently affect prevalence of STEC in various beef products. Hussein and Bollinger (2005b) evaluated published reports in the past 3 decades on STEC prevalence in beef. With regard to *E. coli* O157, the results showed prevalence rates ranging from 0.01 to 43.4% in packing plants, from 0.1 to 54.2% in supermarkets, and an average of 2.4% in fast food restaurants. In general, the prevalence rates of *E. coli* O157 ranged from 0.1 to 54.2% in ground beef, from 0.1 to 4.4% in sausage, from 1.1 to 36.0% in unspecified retail cuts, and from 0.01 to 43.4% in whole carcasses. In 57% of the *E. coli* O157 studies evaluated by Hussein and Bollinger (2005b), the beef samples were tested only for *E. coli* O157:H7. This was due to the availability of simple methods to detect this serotype (Bettelheim, 2003), which is known for its high virulence (CDC, 2003). It is worth noting that in the remaining 43% of the studies, the *E. coli* O157 isolates were not typed for the H antigen. In general, *E. coli* O157:H7 and O157:H$^-$ were detected on the whole carcass and were isolated from various beef products. These serotypes are known to cause major outbreaks and sporadic cases of human illnesses, including HC and HUS (CDC, 2003). Hussein and Bollinger (2005b) showed increased prevalence rates of *E. coli* O157 in recent years, which could be explained by the development and adaptation of more sensitive methods (e.g., immunomagnetic separation) to detect *E. coli* O157 strains (Chapman et al., 2001). Methods designed to detect only *E. coli* O157 isolates, however, usually underestimate the true prevalence of STEC (Read et al., 1990).

In the same evaluation, Hussein and Bollinger (2005b) found nonO157 STEC to be more prevalent in beef products than *E. coli* O157. The prevalence rates of nonO157 STEC ranged from 1.7 to 58.0% in packing plants, from 3.0 to 62.5% in supermarkets, and an average of 3.0% in fast food restaurants. In general, the prevalence rates of nonO157 STEC ranged from 2.4 to 30.0% in ground beef, from 17.0 to 49.2% in sausage, from 8.6 to 49.6% in unspecified retail cuts, and from 1.7 to 58.0% in whole carcasses. Testing other beef products such as steaks and ground veal revealed prevalence rates of 19.0% (Zhao et al., 2001) and 62.5% (Samadpour et al., 1994), respectively.

PATHOGENICITY OF STEC OF BEEF CATTLE ORIGIN

For 23 yr, *E. coli* O157:H7 has been recognized (Riley et al., 1983) as the cause of major outbreaks of human illnesses in North America. Over 50% of the nonO157 STEC strains are also known for their pathogenicity (WHO, 1998). Some of these strains have caused major outbreaks of human illnesses worldwide (Mariani-Kurkdjian et al., 1993; Karch et al., 1997; Morabito et al., 1998). Examples of these include *E. coli* O26:H11, O26:H$^-$, O91:H10, O91:H21, O103:H2, O103:H$^-$, O111:H2, O111:H8, and O111:H$^-$ (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006). It is important to note that not all STEC strains are harmful to humans and pathogenicity of a STEC strain depends on production of key virulence factors. Pathogenic STEC strains are often referred to as enterohemorrhagic *E. coli* (**EHEC**) and are known to produce 1 or 2 toxins that resemble those of *Shigella dysenteriae* (O'Brien and Holmes, 1987). These are Shiga Toxin 1 (**Stx1**) and Shiga Toxin 2 (**Stx2**). Because of their toxic effects on Vero (African green monkey kidney) cells (Konowalchuk et al., 1977), pathogenic STEC strains are also known as verotoxin-producing *E. coli*.

Although Stx1 and Stx2 are different proteins, encoded by different genes (stx_1 and stx_2, respectively), their biological activities are similar (Acheson and Keusch, 1996; Neill, 1997). These activities involve depurinating specific residues of the host cell's ribosomes, blocking the binding of aminoacyl tRNA to the ribosomes, and inhibiting protein synthesis (Saxena et al., 1989). The toxins also bind to and damage the endothelial cells in the intestine, kidney, and brain (Acheson and Keusch, 1996). This results in formation of tiny clots and other damage in capillary beds within the kidney (Acheson and Keusch, 1996). Various STEC strains are known to produce different toxins (Bettel-

Table 1. Serotypes or serogroups of Shiga toxin-producing *Escherichia coli* (STEC) isolated from beef cattle[1]

Health category and related isolates
Caused hemolytic uremic syndrome[2]
O2:H5, O2:H6, O2:H7, O2:H29, O5:H$^-$,[3] O6:H$^-$, O8:H2, O8:H19, O8:H21, O20:H19, O22:H8, O25:H2, O26:H11, O26:H$^-$, O26:HUT[4] (Kijima-Tanaka et al., 2005), O45:H2, O49:H$^-$, O55:H$^-$, O84:H$^-$, O86:H$^-$ (Zweifel et al., 2005), O91:H10, O91:H21, O91:H$^-$, O98:H$^-$, O103:H2, O103:H$^-$, O105:H18, O105ac:H18,[5] O111:H8, O111:H$^-$, O112ac:H19,[5] O113:H21, O118:H16, O118:H$^-$, O119:H2, O119:H6, O121:H19, O125:H$^-$, O128:H2 (Bollinger et al., 2005), O128ab:H2,[6] O145:H25, O145:H28, O145:H$^-$, O146:H21, O153:H25, O154:H$^-$, O157:H7, O157:H$^-$, O161:H$^-$, O163:H19, O165:H25, O165:H$^-$, O171:H$^-$, O172:H$^-$, O174:H2,[7] O174:H21, O174:H$^-$, O177:H$^-$, OR:H4,[7] OR:H25, OR:H$^-$, OUT:H2,[8] OUT:H11, OUT:H25 (Sheng et al., 2005), and OUT:H$^-$
Caused other illnesses[9]
O1:H2 (Bollinger et al., 2005), O1:H20, O2:H27 (Zweifel et al., 2005), O8:H$^-$, O8:HUT, O15:H$^-$, O20:H7, O22:H16, O22:H$^-$, O26:H2, O26:H21 (Kijima-Tanaka et al., 2005), O26:H32, O28:H$^-$, O39:H8, O45:H$^-$, O70:H11, O74:H$^-$, O75:H8, O76:H7, O77:H18, O82:H8, O84:H2, O88:H$^-$ (Kijima-Tanaka et al., 2005), O91:H14, O91:HUT, O103:H25, O104:H7, O112:H21, O113:H4, O113:H7, O113:H$^-$, O117:H7, O117:H19, O119:H$^-$, O126:H20, O128ab:H8, O128:H12, O128:HUT, O132:H$^-$, O141:H$^-$, O146:H28, O146:H$^-$, O150:H$^-$, O156:H25, O163:H$^-$, O171:H2, OR:H19, OR:HUT, OUT:H1, OUT:H4, OUT:H7, OUT:H8, OUT:H10, OUT:H14 (Zweifel et al., 2005), OUT:H16, OUT:H18, OUT:H19, OUT:H21, OUT:H28, OUT:H33, OUT:H41, and OUT:HUT
Did not cause illnesses
O1:H18, O1:H45 (Kijima-Tanaka et al., 2005), O2 (Shaw et al., 2004; Renter et al., 2005), O2:H4, O2:H8, O2:H21 (Zweifel et al., 2005), O2:H25, O2:H26, O2:H45 (Zweifel et al., 2005), O2:H$^-$, O3:H7, O3:H12, O4:H4, O5 (Renter et al., 2005), O5:H7, O5:H27, O6 (Renter et al., 2005), O6:H10, O6:H34, O6:H49, O7 (Renter et al., 2005), O7:H10, O8 (Shaw et al., 2004; Renter et al., 2005), O8:H5, O8:H8, O8:H16, O8:H20 (Zweifel et al., 2005), O8:H25, O10, O11:H14, O11:H$^-$, O15 (Shaw et al., 2004; Renter et al., 2005), O15:H16 (Zweifel et al., 2005), O15:H21, O15:HUT (Kijima-Tanaka et al., 2005), O16:H2, O16:H21, O20 (Shaw et al., 2004), O20:H16, O20:H41, O20:H44, O20:HUT, O22 (Renter et al., 2005), O22:H7, O22:H25, O22:HUT, O23:H15, O25, O25:H19, O25:H21, O25:HUT, O26, O28ac:H4,[5] O28:H8, O28ac:H21, O28ac:H$^-$, O29 (Renter et al., 2005), O32:H7, O37:H10, O38 (Renter et al., 2005), O38:HUT, O39 (Renter et al., 2005), O39:H49, O39:H$^-$, O40:H21, O42:H25, O43:H2, O44:H15, O45:H8, O46:H11 (Kijima-Tanaka et al., 2005), O46:H38, O46:HUT (Kijima-Tanaka et al., 2005), O51:H$^-$, O54:H2, O55:H2, O68:H$^-$, O69 (Renter et al., 2005), O70:H8, O74 (Renter et al., 2005), O74:H19, O74:H28, O74:H42, O74:H52, O74:HUT, O75, O75:H1, O76:H2, O76:H21, O77:H39, O79:H19, O79:H$^-$, O79:HUT, O81:H31, O82:H40, O83:H7, O84 (Shaw et al., 2004; Renter et al., 2005), O84:H8, O86, O86:H2 (Bollinger et al., 2006), O86:H19 (Bollinger et al., 2005), O87, O87:H8, O87:H16, O87:H31, O88 (Renter et al., 2005), O88:H21, O88:HUT, O90:H24, O91 (Shaw et al., 2004; Renter et al., 2005), O91:H8, O91:H49, O93:H19, O96 (Renter et al., 2005), O96:H19, O98 (Renter et al., 2005), O101:H40, O102:H21, O103, O103:H11 (Kijima-Tanaka et al., 2005), O103:H14, O105:H8, O105:H$^-$, O106 (Renter et al., 2005), O106:H42, O108 (Renter et al., 2005), O108:H2, O108:H7, O109, O109:H16, O109:H$^-$, O110:H2, O110:H40, O111, O111:H11, O111:H16, O111:H21 (Zweifel et al., 2005), O112:H2, O112:H7, O113 (Shaw et al., 2004; Renter et al., 2005), O113:H11, O113:H19, O113:H27, O114:H$^-$, O115 (Renter et al., 2005), O116 (Renter et al., 2005), O116:H11 (Zweifel et al., 2005), O116:H21, O116:H28, O116:H$^-$, O116:HUT, O117 (Renter et al., 2005), O117:H16 (Zweifel et al., 2005), O117:H21, O119:H16, O119:H17, O119:H18, O119:H25, O119:H40, O119:HUT, O120, O121 (Renter et al., 2005), O121:H7, O123:H2, O123:H8, O123:H38, O124:H19, O125:H2, O125:H16 (Bollinger et al., 2006), O125:H19 (Bollinger et al., 2005; 2006), O125:H27 (Bollinger et al., 2005), O125:H28 (Bollinger et al., 2005), O125:H47, O125:HUT (Bollinger et al., 2005), O126 (Renter et al., 2005), O126:H7, O126:H28, O127:H2 (Bollinger et al., 2006), O127:H19 (Bollinger et al., 2006), O127:H28 (Bollinger et al., 2005), O128ab (Shaw et al., 2004), O128:H16 (Bollinger et al., 2006), O128:H20 (Bollinger et al., 2005), O128ab:H21, O130 (Renter et al., 2005), O130:H11, O130:H38, O130:H43, O132 (Renter et al., 2005), O132:H2, O132:H18, O136 (Renter et al., 2005), O136:H1, O136:H2 (Zweifel et al., 2005), O136:H12, O136:H16, O136:H$^-$ (Zweifel et al., 2005), O136:HUT (Bollinger et al., 2006), O138:H$^-$, O140:H32, O141 (Renter et al., 2005), O141:H7, O141:H8, O142 (Renter et al., 2005), O143:H2, O145 (Renter et al., 2005), O146 (Renter et al., 2005), O146:H1, O148:H8 (Zweifel et al., 2005), O149:H19, O149:HUT, O150 (Renter et al., 2005), O150:H8, O152:H7, O152:H$^-$, O153 (Renter et al., 2005), O153:H8, O153:H19, O153:H21, O153:HR,[10] O153:HUT, O156:H1, O156:H4, O156:HUT, O157, O157:H2, O157:H8, O157:H12, O157:H19, O157:H25, O157:H27, O157:H38, O157:H43, O157:H45, O157:HUT, O158:H28 (Bollinger et al., 2005), O158:HUT (Bollinger et al., 2005), O159 (Renter et al., 2005), O159:H12, O159:H28, O159:HUT, O160:H10, O160:H21, O160:H38, O160:H$^-$, O161:H2, O161:H19, O161:HUT, O162 (Shaw et al., 2004), O162:H7, O162:H27, O163 (Renter et al., 2005), O165:H8, O166:H2 (Bollinger et al., 2005), O166:H6 (Bollinger et al., 2006), O166:H20 (Bollinger et al., 2005), O168 (Shaw et al., 2004), O168:H8, O171 (Renter et al., 2005), O171:H38, O172 (Renter et al., 2005), O172:H16, O172:H21, O174:H8, O174:H40, O174:H43, O174:HUT, O175:H8, O178:H19, O182:H21 (Zweifel et al., 2005), O211:H7, OR (Renter et al., 2005), OR:H8, OR:H10, OR:H12, OR:H18, OR:H27, OR:H31, OR:H32, OR:H34, OR:H39, OX3[11] (Renter et al., 2005), OX7[12] (Renter et al., 2005), OX7:H16, OX13[12] (Renter et al., 2005), OX18[12] (Renter et al., 2005), OX25[12] (Renter et al., 2005), E2981:H$^-$,[13] E11362:H11,[13] E11362:H21, E11362:H$^-$, E40874[13] (Shaw et al., 2004), E54071[13] (Shaw et al., 2004), E54071:H19, OUT (Shaw et al., 2004), OUT:H5, OUT:H20 (Bollinger et al., 2005), OUT:H24, OUT:H27, OUT:H29, OUT:H30, OUT:H32, OUT:H34, OUT:H37, OUT:H38, OUT:H40, OUT:H42, OUT:H49, and OUT:HR.

[1]Unless otherwise indicated, the STEC serotypes or serogroups and their origin are listed in Hussein and Bollinger (2005a).

[2]The STEC serotypes were isolated from humans suffering from hemolytic uremic syndrome (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006).

[3]A nonmotile isolate.

[4]An untypeable H antigen.

[5]Within each of the O28, O105, and O112 serogroups, certain antigenic relationships are represented by 'a,' a common factor and 'c,' a specific factor (Lior, 1994).

[6]Within the O128 serogroup, certain antigenic relationships are represented by 'a,' a common factor and 'b,' a specific factor (Lior, 1994).

[7]A rough O antigen.

[8]An untypeable O antigen.

[9] The STEC serotypes were isolated from humans suffering from a wide range of illnesses such as mild diarrhea, bloody diarrhea, abdominal pain, ulcerative colitis, hemorrhagic colitis, and thrombotic thrombocytopenic purpura (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006).

[10]A rough H antigen.

[11]The O174 antigen was formerly designated as OX3.

[12]OX7, OX13, OX18, and OX25 are provisional designations for new O serogroups.

[13]E2981, E11362, E40874, and E54071 are new provisional serogroups.

Table 2. Serotypes or serogroups of Shiga toxin-producing *Escherichia coli* (STEC) isolated from beef products[1]

Health category and related isolates
Caused hemolytic uremic syndrome[2]
O2:H29, O4:H$^-$,[3] O5:H$^-$, O8:H19, O14:H$^-$, O20:H19, O22:H5, O22:H8, O23:H$^-$, O26:H11, O45:H2, O50:H7, O84:H$^-$, O91:H21, O91:H$^-$, O103:H2, O103:H21, O104:H$^-$, O105:H18, O111:H$^-$, O113:H21, O117:H4, O121:H19, O125:H$^-$, O128:H2, O128ab:H2,[4] O128:H7, O137:H41, O145:H$^-$, O146:H21, O153:H25, O157:H7, O157:H$^-$, O163:H19, O165:H25, O165:H$^-$, O172:H$^-$, O174:H2, O174:H21, OR:H$^-$,[5] OUT:H2,[6] OUT:H11, and OUT:H$^-$
Caused other illnesses[7]
O1:H20, O6:H31, O8:H9, O8:H$^-$, O8:HUT,[8] O15:H27, O15:H$^-$, O17:H18, O22:H16, O22:H$^-$, O60:H19, O62:H$^-$, O74:H$^-$, O75:H8, O82:H8, O91:H14, O110:H$^-$, O113:H4, O113:H$^-$, O117:H7, O146:H28, O171:H2, OR:H2, OR:H7, OR:H21, OUT:H4, OUT:H7, OUT:H8, OUT:H12, OUT:H16, OUT:H18, OUT:H19, OUT:H21, OUT:H28, OUT:H47, and OUT:HUT
Did not cause illnesses
O1, O2, O3, O4:H21, O6, O6:H10, O6:H34, O7:H16, O7:H$^-$, O8, O8:H16, O8:H30, O10, O15, O18ac,[9] O20, O20:H12, O21, O22:H4, O22:H54, O22:HUT, O23:H15, O25, O25:H21, O26, O27:H21, O28:H4, O30:H$^-$, O38:H30, O39, O39:H49, O43:H38 (Li et al., 2005), O45, O46:H8, O46:H38, O46:H$^-$, O54:H2, O55, O55:H9, O56:H56, O57:H$^-$, O59, O62:H8, O65:H48, O68, O70, O73:H16, O73:H31, O73:H$^-$, O74, O74:H37, O74:H39, O75, O79:H$^-$, O81, O81:H26, O84, O86 (Hazarika et al., 2004), O87, O87:H16, O88, O88:H21, O88:H25, O88:H49, O91, O98 (Hazarika et al., 2004), O100:H$^-$, O103, O104, O104:H12, O106, O107:H7, O109, O110, O110:HUT, O111, O111:H7, O111:H16, O112:H2, O113, O113:H19, O116:H21, O116:H$^-$, O117, O117:H8, O119, O121, O123, O125ab:H$^-$,[4] O128, O128:H27, O128:H35, O131, O132, O136, O138:H$^-$, O139, O139:H19, O142, O142:H38, O144:H2, O145, O148:H8, O149:H10, O149:H45, O150:H8, O151:H8, O151:H12, O153, O153:H8, O157, O159:H7, O160, O162, O162:H7, O163, O165, O166:H$^-$, O168, O168:H8, O171, O171:H25, O172, O172:H16, O174,[10] O174:H8, OR, OR:H14, OR:H23, OR:H31, OR:H42, OR:H47, OR:H48, OX6,[11] OX25,[11] OC70:H49,[11] OC86:H49,[11] OUT, OUT:H5, OUT:H6, OUT:H9, and OUT:H23

[1]Unless otherwise indicated, the STEC serotypes or serogroups and their origin are listed in Hussein and Bollinger (2005b).
[2]The STEC serotypes were isolated from humans suffering from hemolytic uremic syndrome (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006).
[3]A nonmotile isolate.
[4]Within each of the O125 and O128 serogroups, certain antigenic relationships are represented by "a," a common factor and "b," a specific factor (Lior, 1994).
[5]A rough O antigen.
[6]An untypeable O antigen.
[7]The STEC serotypes were isolated from humans suffering from a wide range of illnesses such as mild diarrhea, bloody diarrhea, abdominal pain, ulcerative colitis, hemorrhagic colitis, and thrombotic thrombocytopenic purpura (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006).
[8]An untypeable H antigen.
[9]Within the O18 serogroup, certain antigenic relationships are represented by "a," a common factor and "c," a specific factor (Lior, 1994).
[10]The O174 antigen was formerly designated as OX3.
[11]OX6, OX25, OC70, and OC86 are provisional designations for new O serogroups.

heim, 2003; Blanco et al., 2003), and the ability of a specific strain to cause human illnesses depends on its toxin production (Karmali et al., 1985; Jacewicz et al., 2000). Human illnesses, however, have been caused by STEC strains producing Stx1, Stx2, or both toxins (Lior, 1994; Willshaw et al., 1997; Bonnet et al., 1998).

Pathogenic STEC strains not only produce Shiga toxins but also can produce other virulence factors that may increase the severity of human illnesses (Paton and Paton, 2000). These factors include intimin and enterohemolysin, which are responsible for the intimate attachment to the intestinal surface and enterocyte damage, respectively (Saunders et al., 1999; Donnenberg, 2002). These virulence factors (i.e., intimin and enterohemolysin) are encoded by the *E. coli* attaching and effacing (***eae***) and enterohemolysin (***ehxA***) genes, respectively). These genes are found in virtually all *E. coli* O157 strains (Neill, 1997) and appear to be more common in pathogenic nonO157 STEC strains (Beutin et al., 1994). Because some STEC strains lacking *ehxA* and *eae* were shown to cause human illnesses (Neill, 1997), these genes do not appear to be absolutely required for pathogenicity. Thus, it was suggested that each STEC strain should be considered a potential EHEC (Bürk et al., 2002). However, many STEC strains still lack association with human illnesses.

Among the STEC strains that have been isolated from humans with illnesses, a subset of EHEC strains has been found (Levine, 1987) to carry common sets of virulence genes that encode factors for attachment to the host cells, elaboration of effector molecules, and productions of either or both toxins (Stx1 and Stx2). The sets of the virulence genes are found in the locus of enterocyte attachment pathogenicity island, lambdoid bacteriophages, and a large virulence associated plasmid (Newland et al., 1985; McDaniel et al., 1995; Schmidt et al., 1997). Population genetic analysis revealed EHEC strains to compose 2 divergent lineages, termed EHEC 1 and EHEC 2, that are only distantly related but apparently experience similar pathways of virulence gene acquisition (Whittam et al., 1993; McGraw et al., 1999; Reid et al., 2000). The EHEC 1 lineage is comprised solely of a geographically disseminated cluster of strains with related genotypes bearing O157:H7 and O157:H$^-$ serotypes, whereas the EHEC 2 lineage is serotypically and genotypically more diverse. New evidence indicated that the *E. coli* O157:H7 lineage of EHEC is a geographically disseminated complex of highly related genotypes that share common ancestry (Kim et al., 2001). Additionally, the DNA sequence analysis of representative polyphyletic markers showed that genome

diversity accrued through random drift and bacteriophage-mediated event (Kim et al., 2001).

Evaluation of published reports on STEC shedding by beef cattle in the past 25 yr (Table 1) revealed the isolation of strains belonging to 121 O serogroups, 4 new E serogroups, and 373 serotypes. Of these STEC serotypes, 65 were isolated from HUS patients and an additional 62 are known to cause human illnesses such as mild or bloody diarrhea, abdominal cramps, and HC (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006). Evaluation of published reports during the same period on STEC contamination of beef (Table 2) revealed isolation of strains belonging to 98 O serogroups, 2 new provisional O serogroups, and 162 serotypes. Of these, 43 were isolated from HUS patients and an additional 36 are known to cause other human illnesses (WHO, 1998; Blanco et al., 2003; Bettelheim, 2006).

CONCLUSIONS

Shiga toxin-producing *E. coli* are known to cause human illnesses ranging from mild diarrhea to the life-threatening HUS. Because a large number of human illness outbreaks were traced to beef consumption, the roles of beef cattle and their edible products in human infection were evaluated. Worldwide testing of beef cattle and their products revealed high prevalence rates for *E. coli* O157 and other nonO157 serotypes known for their high virulence. Thus, beef cattle are considered reservoirs for these foodborne pathogens. These findings emphasized the critical need for long-term strategies to assure beef safety. Current and future strategies should include educational programs to bring awareness of the STEC problem to beef farmers, ranchers, processors, and consumers. Developing and implementing pre- and postharvest control measures to effectively decrease carriage of these pathogens by beef cattle and to eliminate contamination of their products during processing are essential steps toward sustaining a competitive beef industry.

LITERATURE CITED

Acheson, D. W. K., and G. T. Keusch. 1996. Which Shiga toxin-producing types of *E. coli* are important? ASM News 62:302–306.

Al-Saigh, H., C. Zweifel, J. Blanco, J. E. Blanco, M. Blanco, M. A. Usera, and R. Stephan. 2004. Fecal shedding of *Escherichia coli* O157, *Salmonella,* and *Campylobacter* in Swiss cattle at slaughter. J. Food Prot. 67:679–684.

Anonymous. 2001. Non-O157 Shiga toxin-producing *Escherichia coli* (STEC). http://www.nzfsa.govt.nz/science-technology/data-sheets/non-o157-stec.pdf Accessed Nov. 4, 2004.

Bacon, R. T., K. E. Belk, J. N. Sofos, and G. C. Smith. 2000. Incidence of *Escherichia coli* O157:H7 on hide, carcass and beef trimmings samples collected from United States packing plants. http://www.amif.org/pdf/AMIF%20Executive%20Summary%20Carcass%20Sampling%202000.pdf Accessed Dec. 22, 2006.

Barkocy-Gallagher, G. A., T. M. Arthur, M. Rivera-Betancourt, X. Nou, S. D. Shackelford, T. L. Wheeler, and M. Koohmaraie. 2003. Seasonal prevalence of Shiga toxin-producing *Escherichia coli,* including O157:H7 and non-O157:H7 serotypes, and Salmonella in commercial beef processing plants. J. Food Prot. 66:1978–1986.

Bell, R. G. 1997. Distribution and sources of microbial contamination on beef carcasses. J. Appl. Microbiol. 82:292–300.

Besser, T. E., D. D. Hancock, L. C. Pritchett, E. M. McRae, D. H. Rice, and P. I. Tarr. 1997. Duration of detection of fecal excretion of *Escherichia coli* O157:H7 in cattle. J. Infect. Dis. 175:726–729.

Bettelheim, K. A. 2003. Non-O157 verotoxin-producing *Escherichia coli:* A problem, paradox, and paradigm. Exp. Biol. Med. 228:333–344.

Bettelheim, K. A. 2006. Serotypes of VTEC: The VTEC Table. http://www.microbionet.com.au/vtectable.htm Accessed Jan. 9, 2006.

Beutin, L., D. Geier, H. Steinrück, S. Zimmermann, and F. Scheutz. 1993. Prevalence and some properties of verotoxin (Shiga-like toxin)-producing *Escherichia coli* in seven different species of healthy domestic animals. J. Clin. Microbiol. 31:2483–2488.

Beutin, L., S. Aleksic, S. Zimmermann, and K. Gleier. 1994. Virulence factors and phenotypical traits of verotoxigenic strains of *Escherichia coli* isolated from human patients in Germany. Med. Microbiol. Immunol. (Berl.) 183:13–21.

Beutin, L., D. Geier, S. Zimmermann, S. Aleksic, H. A. Gillespie, and T. S. Whittam. 1997. Epidemiological relatedness and clonal types of natural populations of *Escherichia coli* strains producing Shiga toxins in separate populations of cattle and sheep. Appl. Environ. Microbiol. 63:2175–2180.

Beutin, L., D. Geier, S. Zimmermann, and H. Karch. 1995. Virulence markers of Shiga-like toxin producing *Escherichia coli* strains originating from healthy domestic animals of different species. J. Clin. Microbiol. 33:631–635.

Bielaszewska, M., S. Herbert, L. Almut, P. Rita, R. Wolfgang, T. Helmut, C. Alois, J. Jan, B. Kveta, and K. Helge. 2000. Cattle can be a reservoir of sorbitol-fermentation Shiga toxin-producing *Escherichia coli* O157:H$^-$ strains and a source of human disease. J. Clin. Microbiol. 38:3470–3473.

Blanco, J., M. Blanco, J. E. Blanco, A. Mora, E. A. González, M. I. Bernárdez, M. P. Alonso, A. Coira, A. Rodriguez, J. Rey, J. M. Alonso, and M. A. Usera. 2003. Verotoxin-producing *Escherichia coli* in Spain: Prevalence, serotypes, and virulence genes of O157:H7 and non-O157 VTEC in ruminants, raw beef products, and humans. Exp. Biol. Med. 228:345–351.

Bollinger, L. M. 2004. Effects of season and animal factors on prevalence of Shiga toxin-producing *Escherichia coli* in beef cattle. MS Thesis Univ. Nevada, Reno.

Bollinger, L. M., H. S. Hussein, M. R. Hall, and E. R. Atwill. 2006. Isolation, characterization, and potential pathogenicity of Shiga toxin-producing *Escherichia coli* from beef cattle in California during winter and spring. Abstract # Z-014 in Abstracts of the 106th Gen. Meet. Am. Soc. Microbiol (CD Edition). Am. Soc. Microbiol., Washington, DC.

Bollinger, L. M., H. S. Hussein, T. Sakuma, M. R. Hall, and E. R. Atwill. 2005. Isolation and characterization of Shiga toxin-producing *Escherichia coli* from beef cattle. Abstract # Z-024 in Abstracts of the 105th Gen. Meet. Am. Soc. Microbiol (CD Edition). Am. Soc. Microbiol., Washington, DC.

Bonnet, R., B. Souweine, G. Gauthier, C. Rich, V. Livrelli, J. Sirot, B. Joly, and C. Forestier. 1998. Non-O157:H7 Stx2-producing *Escherichia coli* strains associated with sporadic cases of hemolytic-uremic syndrome in adults. J. Clin. Microbiol. 36:1777–1780.

Bürk, C., I. G. B. Braumiller, H. Becker, and E. Märtlbauer. 2002. Nuclease fluorescence assay for the detection of verotoxin genes in raw milk. Lett. Appl. Microbiol. 35:153–156.

Caprioli, A., I. Luzzi, F. Rosmini, C. Resti, A. Edefonti, F. Perfumo, C. Farina, A. Goglio, A. Gianviti, and G. Rizzoni. 1994. Community wide outbreak of hemolytic-uremic syndrome associated with non-O157 verocytotoxin-producing *Escherichia coli.* J. Infect. Dis. 169:208–211.

Caprioli, A., A. Nigrelli, R. Gatti, M. Zavanella, A. M. Blando, F. Minelli, and G. Donelli. 1993. Characterization of verocytotoxin-producing *Escherichia coli* from pigs and cattle in northern Italy. Vet. Rec. 133:323–324.

CDC. 1993. Update: Multistate outbreak of *Escherichia coli* O157:H7 infections from hamburgers—Western United States, 1992–1993. Morb. Mortal. Wkly. Rep. 42:258–263.

CDC. 1995. *Escherichia coli* O157:H7 linked to commercially distributed dry-cured salami, Washington and California 1994. Morb. Mortal. Wkly. Rep. 44:157–160.

CDC. 2003. *E. coli* O157 outbreak summaries. http://www.cdc.gov/foodborneoutbreaks/ecoli/STEC2002.pdf Accessed Dec. 22, 2006.

Chapman, P. A., M. Ellin, and R. Ashton. 2001. A comparison of immunomagnetic separation and culture, Reveal and VIP for the detection of *E. coli* O157 in enrichment cultures of naturally contaminated raw beef, lamb, and mixed meat products. Lett. Appl. Microbiol. 32:171–175.

Cieslak, P. R., T. J. Barrett, and P. M. Griffin. 1993. *Escherichia coli* O157:H7 infection from a manured garden. Lancet 342:367.

Čižek, A., P. Alexa, I. Literák, J. Hamřík, P. Novák, and J. Smola. 1999. Shiga toxin-producing *Escherichia coli* O157 in feedlot cattle and Norwegian rats from a large-scale farm. Lett. Appl. Microbiol. 28:435–439.

Cobbold, R. N., D. H. Rice, M. Szymanski, D. R. Call, and D. D. Hancock. 2004. Comparison of Shiga-toxigenic *Escherichia coli* prevalences among dairy, feedlot, and cow-calf herds in Washington State. Appl. Environ. Microbiol. 70:4375–4378.

Cowden, J. M. 1997. Scottish outbreak of *Escherichia coli* O157, November-December 1996. Euro Surveill. 2:1–2.

Crump, J. A., A. C. Sulka, A. J. Langer, C. Schaben, A. S. Crielly, R. Gage, M. Baysinger, M. Moll, G. Withers, D. M. Toney, S. B. Hunter, R. M. Hoekstra, S. K. Wong, P. M. Griffin, and T. J. Van Gilder. 2002. An outbreak of *Escherichia coli* O157:H7 infections among visitors to a dairy farm. N. Engl. J. Med. 347:555–560.

Donnenberg, M. S. 2002. VIII. Infections due to *Escherichia coli* and other enteric gram-negative bacilli. WebMD® Scientific American® Medicine. http://online.statref.com/document.aspx?fxid=48&docid=1046 Accessed Jun. 25, 2003.

Doyle, M. P., and J. L. Schoeni. 1987. Isolation of *Escherichia coli* O157:H7 from retail fresh meats and poultry. Appl. Environ. Microbiol. 53:2394–2396.

Elder, R. O., J. E. Keen, G. R. Siragusa, G. A. Barkocy-Gallagher, M. Koohmaraie, and W. W. Laegreid. 2000. Correlation of enterohemorrhagic *Escherichia coli* O157 prevalence in feces, hides, and carcasses of beef cattle during processing. Proc. Natl. Acad. Sci. USA 97:2999–3003.

Ezawa, A., F. Gocho, K. Kawata, T. Takahashi, and N. Kikuchi. 2004. High prevalence of enterohemorrhagic *Escherichia coli* (EHEC) O157 from cattle in selected regions of Japan. J. Vet. Med. Sci. 66:585–587.

Fitzpatrick, M. M., V. Shah, R. S. Trompeter, M. H. Dillon, and T. M. Barrett. 1991. Long term renal outcome of childhood haemolytic uraemic syndrome. BMJ 303:489–492.

Galland, J. C., D. R. Hyatt, S. S. Crupper, and D. W. Acheson. 2001. Prevalence, antibiotic susceptibility, and diversity of *Escherichia coli* O157:H7 isolates from a longitudinal study of beef cattle feedlots. Appl. Environ. Microbiol. 67:1619–1627.

Gannon, V. P. J., T. A. Graham, R. King, P. Michel, S. Read, K. Ziebell, and R. P. Johnson. 2002. *Escherichia coli* O157:H7 infection in cows and calves in a beef cattle herd in Alberta, Canada. Epidemiol. Infect. 129:163–172.

Geue, L., M. Segura-Alvarez, F. J. Conraths, T. Kuczius, J. Bockemuhl, H. Karch, and P. Gallien. 2002. A long-term study on the prevalence of Shiga toxin-producing *Escherichia coli* (STEC) on four German cattle farms. Epidemiol. Infect. 129:173–185.

Gioffré, A., L. Meichtri, E. Miliwebsky, A. Baschkier, G. Chillemi, M. I. Romano, S. Sosa Estani, A. Cataldi, R. Rodríguez, and M. Rivas. 2002. Detection of Shiga toxin-producing *Escherichia coli* by PCR in cattle in Argentina. Evaluation of two procedures. Vet. Microbiol. 87:301–313.

Griffin, P. M., and R. V. Tauxe. 1991. The epidemiology of infections caused by *Escherichia coli* O157:H7, other enterohemorrhagic *E. coli,* and the associated hemolytic uremic syndrome. Epidemiol. Rev. 13:60–98.

Hancock, D. D., T. E. Besser, M. L. Kinsel, P. I. Tarr, D. H. Rice, and M. G. Paros. 1994. The prevalence of *Escherichia coli* O157:H7 in dairy and beef cattle in Washington state. Epidemiol. Infect. 113:199–207.

Hancock, D. D., D. H. Rice, L. A. Thomas, D. A. Dargatz, and T. E. Besser. 1997. Epidemiology of *Escherichia coli* O157 in feedlot cattle. J. Food Prot. 60:462–465.

Hazarika, R. A., D. K. Singh, K. N. Kapoor, R. K. Agarwal, A. B. Pandey, and D. N. Rajkumar. 2004. Detection and characterization of verotoxin-producing *Escherichia coli* (VTEC) isolated from buffalo meat. J. Food Safety 24:281–290.

Henning, P. H., E. B. Tham, A. A. Martin, T. H. Beare, and K. F. Jureidini. 1998. Haemolytic-uraemic syndrome outbreak caused by *Escherichia coli* O111:H$^-$: Clinical outcomes. Med. J. Aust. 168:552–555.

Herriott, D. E., D. D. Hancock, W. E. Keene, and D. H. Rice. 1994. Raw milk associated *E. coli* O157:H7 outbreaks in Oregon. Pages FS17–FS21 in Proc. 8th Int. Congr. Anim. Hygiene, Int. Soc. Anim. Hygiene, St. Paul, MN.

Hussein, H. S., and L. M. Bollinger. 2005a. Prevalence of Shiga toxin-producing *Escherichia coli* in beef cattle. J. Food Prot. 68:2224–2241.

Hussein, H. S., and L. M. Bollinger. 2005b. Prevalence of Shiga toxin-producing *Escherichia coli* in beef. Meat Sci. 71:676–689.

Hussein, H. S., and T. Sakuma. 2005. Prevalence of Shiga toxin-producing *Escherichia coli* in dairy cattle and their products. J. Dairy Sci. 88:450–465.

Hussein, H. S., B. H. Thran, M. R. Hall, W. G. Kvasnicka, and R. C. Torell. 2003. Verotoxin-producing *Escherichia coli* in culled beef cows grazing rangeland forages. Exp. Biol. Med. 228:352–357.

Jacewicz, M. S., H. Trachtman, D. S. Newberg, and D. W. K. Acheson. 2000. Abstr. 100th Gen. Meet. Am. Soc. Microbiol. B-102:64. (Abstr.)

Jenkins, C., M. C. Pearce, H. Chart, T. Cheasty, G. A. Willshaw, G. J. Gunn, G. Dougan, H. R. Smith, B. A. Synge, and G. Frankel. 2002. An eight-month study of a population of verocytotoxigenic *Escherichia coli* (VTEC) in a Scottish cattle herd. J. Appl. Microbiol. 93:944–953.

Karch, H., C. Geitz, and H. Schmidt. 1997. Increased incidence of infections with EHEC O103:H2. Notiziaro dell'Istituto Superiore di Sanita 10(3):2.

Karmali, M. A., M. Petric, C. Lim, P. C. Fleming, G. S. Arbus, and H. Lior. 1985. The association between idiopathic hemolytic-uremic syndrome and infection by verotoxin-producing *Escherichia coli.* J. Infect. Dis. 151:775–782.

Khaitsa, M. L., M. L. Bauer, P. S. Gibbs, and G. P. Lardy. 2003. Risk assessment of *Escherichia coli* O157:H7 fecal shedding in North Dakota feedlot cattle. Unified Beef Cattle and Range Research Report. North Dakota State Univ., Fargo.

Khan, A., S. Yamasaki, T. Sato, T. Ramamurthy, A. Pal, S. Datta, N. R. Chowdhury, S. C. Das, A. Sikdar, T. Tsukamoto, S. K. Bhattacharya, Y. Takeda, and G. B. Nair. 2002. Prevalence and genetic profiling of virulence determinants of non-O157 Shiga toxin-producing *Escherichia coli* isolated from cattle, beef, and humans, Calcutta, India. Emerg. Infect. Dis. 8:54–62.

Kijima-Tanaka, M., K. Ishihara, A. Kojima, A. Morioka, R. Nagata, M. Kawanishi, M. Nakazawa, Y. Tamura, and T. Takahashi. 2005. A national surveillance of Shiga toxin-producing *Escherichia coli* in food-producing animals in Japan. J. Vet. Med. B52:230–237.

Kim, J., J. Nietfeldt, J. Ju, J. Wise, N. Fegan, P. Desmarchelier, and A. K. Benson. 2001. Ancestral divergence, genome diversification, and phylogeographic variation in subpopulations of sorbitol-negative, β-glucuronidase-negative enterohemorrhagic *Escherichia coli* O157. J. Bacteriol. 183:6885–6897.

Konowalchuk, J., J. I. Speirs, and S. Stavric. 1977. Vero response to a cytotoxin of *Escherichia coli.* Infect. Immun. 18:775–779.

Lahti, E., M. Eklund, P. Ruutu, A. Siitonrn, L. Rantala, P. Nuorti, and T. Honkanen-Buzalski. 2002. Use of phenotyping and genotyping to verify transmission of *Escherichia coli* O157:H7 from dairy farms. Eur. J. Clin. Microbiol. Infect. Dis. 21:189–195.

Lahti, E., M. Keskimäki, L. Rantala, P. Hyvönen, A. Siitonen, and T. Honkanen-Buzalski. 2001. Occurrence of *Escherichia coli* O157 in Finnish cattle. Vet. Microbiol. 79:239–251.

LeJeune, J. T., T. E. Besser, D. H. Rice, J. L. Berg, R. P. Stillborn, and D. D. Hancock. 2004. Longitudinal study of fecal shedding of *Escherichia coli* O157:H7 in feedlot cattle: Predominance and persistence of specific clonal types despite massive cattle population turnover. Appl. Environ. Microbiol. 70:377–384.

Leomil, L., L. Aidar-Ugrinovich, B. E. C. Guth, K. Irino, M. P. Vettorato, D. L. Onuma, and A. F. P. de Castro. 2003. Frequency of Shiga toxin-producing *Escherichia coli* (STEC) isolates among diarrheic and non-diarrheic calves in Brazil. Vet. Microbiol. 97:103–109.

Leung, P. H. M., W. C. Yam, W. W. S. Ng, and J. S. M. Peiris. 2001. The prevalence and characterization of verotoxin-producing *Escherichia coli* isolated from cattle and pigs in an abattoir in Hong Kong. Epidemiol. Infect. 126:173–179.

Levine, M. M. 1987. *Escherichia coli* that cause diarrhea: Enterotoxigenic, enteropathogenic, enteroinvasive, enterohemorrhagic, and enteroadherent. J. Infect. Dis. 155:377–389.

Li, F., C. Zhao, W. Zhang, S. Cui, J. Meng, J. Wu, and D. Y. Zhang. 2005. Use of ramification amplification assay for detection of *Escherichia coli* O157:H7 and other *E. coli* Shiga toxin-producing strains. J. Clin. Microbiol. 43:6086–6090.

Lior, H. 1994. Classification of *Escherichia coli.* Pages 31–72 in *Escherichia coli* in Domestic Animals and Humans. C. L. Gyles, ed. CAB Int., Wallingford, UK.

López, E. L., M. M. Contrini, M. Sanz, M. R. Viñas, A. Parma, M. F. De Rosa, and T. G. Cleary. 1997. Perspectives in Shiga-like toxin infections in Argentina. J. Food Prot. 60:1458–1462.

Mariani-Kurkdjian, P., E. Denamur, A. Milon, B. Picard, H. Cave, N. Lambert-Zechovsky, C. Loirat, P. Goullet, P. Sansonetti, and J. Elion. 1993. Identification of a clone of *Escherichia coli* O103:H2 as a potential agent of hemolytic uremic syndrome in France. J. Clin. Microbiol. 31:296–301.

Martin, M. L., L. D. Shipman, J. G. Wells, M. E. Potter, K. Hedberg, I. K. Wachsmuth, R. V. Tauxe, J. P. Davis, J. Arnoldi, and J. Tilleli. 1986. Isolation of *Escherichia coli* O157 from dairy cattle associated with two cases of haemolytic uraemic syndrome. Lancet II:1043.

McDaniel, T. K., K. G. Jarvis, M. S. Donnenberg, and J. B. Kaper. 1995. A genetic locus of enterocyte effacement conserved among diverse enterobacterial pathogens. Proc. Natl. Acad. Sci. USA 92:1664–1668.

McEvoy, J. M., A. M. Doherty, M. Finnerty, J. J. Sheridan, L. McGuire, I. S. Blair, D. A. McDowell, and D. Harrington. 2000. The relationship between hide cleanliness and bacterial numbers on beef carcasses at a commercial abattoir. Lett. Appl. Microbiol. 30:390–395.

McEvoy, J. M., A. M. Doherty, J. J. Sheridan, F. M. Thomson-Carter, P. Garvey, L. McGuire, I. S. Blair, and D. A. McDowell. 2003. The prevalence and spread of *Escherichia coli* O157:H7 at a commercial beef abattoir. J. Appl. Microbiol. 95:256–266.

McGraw, E. A., J. Li, R. K. Selander, and T. S. Whittam. 1999. Molecular evolution and mosaic structure of alpha, beta, and gamma intimins of pathogenic *Escherichia coli.* Mol. Biol. Evol. 16:12–22.

Morabito, S., H. Karch, P. Mariani-Kurkdjian, H. Schmidt, F. Minelli, E. Bingen, and A. Caprioli. 1998. Enteroaggregative, Shiga toxin-producing *Escherichia coli* O111:H2 associated with an outbreak of hemolytic-uremic syndrome. J. Clin. Microbiol. 36:840–842.

Morgan, D., C. P. Newman, D. N. Hutchinson, A. M. Walker, B. Rowe, and F. Majid. 1993. Verotoxin producing *Escherichia coli* O157 infections associated with the consumption of yoghurt. Epidemiol. Infect. 111:181–187.

Nataro, J. P., and J. B. Kaper. 1998. Diarrheagenic *Escherichia coli.* Clin. Microbiol. Rev. 11:142–201.

Neill, M. A. 1997. Overview of verotoxigenic *Escherichia coli.* J. Food Prot. 60:1444–1446.

Newland, J. W., N. A. Strockbine, F. F. Miller, A. D. O'Brien, and R. K. Holmes. 1985. Cloning of Shiga-like toxin genes from a toxin converting phage of *Escherichia coli.* Science 230:179–181.

O'Brien, A. D., and R. K. Holmes. 1987. Shiga and Shiga-like toxins. Microbiol. Rev. 51:206–220.

Ogden, I. D., M. MacRae, and N. J. C. Strachan. 2004. Is prevalence and shedding of *E. coli* O157 in beef cattle in Scotland seasonal? FEMS Microbiol. Lett. 233:297–300.

Ohya, T., and H. Ito. 1999. Experimental infection of calves with *Escherichia coli* O157:H7. J. Vet. Med. Sci. 61:1187–1189.

Omisakin, F., M. MacRae, I. D. Ogden, and N. J. C. Strachan. 2003. Concentration and prevalence of *Escherichia coli* O157 in cattle feces at slaughter. Appl. Environ. Microbiol. 69:2444–2447.

Orr, P., B. Lorencz, R. Brown, R. Kielly, B. Tan, D. Holton, H. Clugstone, L. Lugtig, C. Pim, S. MacDonald, G. Hammond, M. Moffatt, J. Spika, D. Manuel, W. Winther, D. Milley, H. Lior, and N. Sinuff. 1994. An outbreak of diarrhea due to verotoxin-producing *Escherichia coli* in the Canadian Northwest Territories. Scand. J. Infect. Dis. 26:675–684.

Padola, N. L., M. E. Sanz, J. E. Blanco, M. Blanco, J. Blanco, A. I. Etcheverria, G. H. Arroyo, M. A. Usera, and A. E. Parma. 2004. Serotypes and virulence genes of bovine Shigatoxigenic *Escherichia coli* (STEC) isolated from a feedlot in Argentina. Vet. Microbiol. 100:3–9.

Paiba, G. A., J. C. Gibbens, S. J. S. Pascoe, J. W. Wilesmith, S. A. Kidd, C. Byrne, J. B. M. Ryan, R. P. Smith, I. M. McLaren, R. J. Futter, A. C. S. Kay, Y. E. Jones, S. A. Chappell, G. A. Willshaw, and T. Cheasty. 2002. Faecal carriage of verocytotoxin-producing *Escherichia coli* O157 in cattle and sheep at slaughter in Great Britain. Vet. Rec. 150:593–598.

Paton, J. C., and A. W. Paton. 2000. Shiga toxigenic *Escherichia coli* infections. Sci. Med. (Phila.) May/June:28–37.

Pavia, A. T., C. R. Nichols, D. P. Green, R. V. Tauxe, S. Mottice, K. D. Greene, J. G. Wells, R. L. Siegler, E. D. Brewer, D. Hannon, and P. A. Blake. 1990. Hemolytic-uremic syndrome during an outbreak of *Escherichia coli* O157:H7 infections in institutions for mentally retarded persons: Clinical and epidemiologic observations. J. Pediatr. 116:544–545.

Pearce, M. C., C. Jenkins, L. Vali, A. W. Smith, H. I. Knight, T. Cheasty, H. R. Smith, G. J. Gunn, M. E. J. Woolhouse, S. G. B. Amyes, and G. Frankel. 2004. Temporal shedding patterns and virulence factors of *Escherichia coli* serogroups O26, O103, O111, O145, and O157 in a cohort of beef calves and their dams. Appl. Environ. Microbiol. 70:1708–1716.

Pradel, N., V. Livrelli, C. De Champs, J. B. Palcoux, A. Reynaud, F. Scheutz, J. Sirot, B. Joly, and C. Forestier. 2000. Prevalence and characterization of Shiga toxin-producing *Escherichia coli* isolated from cattle, food, and children during a one-year prospective study in France. J. Clin. Microbiol. 38:1023–1031.

Read, S. C., C. L. Gyles, R. C. Clarke, H. Lior, and S. McEwen. 1990. Prevalence of verocytotoxigenic *Escherichia coli* in ground beef, pork, and chicken in Southwestern Ontario. Epidemiol. Infect. 105:11–20.

Reid, S. D., C. J. Herbelin, A. C. Brumbaugh, R. K. Selander, and T. S. Whittam. 2000. Parallel evolution of virulence in pathogenic *Escherichia coli.* Nature 406:64–67.

Reid, T. M. S. 2001. A case study of cheese associated *E. coli* O157 outbreaks in Scotland. Pages 201–212 in Verocytotoxigenic *Escherichia coli.* G. Duffy, P. Garvey, and D. McDowell, ed. Food and Nutrition Press Inc., Trumbull, CT.

Reida, P., M. Wolff, H. W. Pohls, W. Kuhlmann, A. Lehmacher, S. Aleksic, H. Karch, and J. Bockemuhl. 1994. An outbreak due to enterohemorrhagic *Escherichia coli* O157:H7 in a children day care center characterized by person-to-person transmission and environmental contamination. Zentralbl. Bakteriol. 281:534–543.

Remuzzi, G. 1987. HUS and TTP: Variable expression of a single entity. Kidney Int. 32:292–308.

Renter, D. G., J. G. Morris, Jr., J. M. Sargeant, L. L. Hungerford, J. Berezowski, T. Ngo, K. Williams, and D. W. K. Acheson. 2005. Prevalence, risk factors, O-serogroups, and virulence profiles of Shiga toxin-producing bacteria from cattle production environments. J. Food Prot. 68:1556–1565.

Ridell, J., and H. Korkeala. 1993. Special treatment during slaughtering in Finland of cattle carrying an excessive load of dung; meat hygienic aspects. Meat Sci. 35:223–228.

Riley, L. W., R. S. Remis, S. D. Helgerson, H. B. McGee, J. G. Well, B. R. Davis, R. J. Hebert, E. S. Olcott, L. M. Johnson, N. T. Hargrett, P. A. Blake, and M. L. Cohen. 1983. Hemorrhagic colitis associated with a rare *Escherichia coli* serotype. N. Engl. J. Med. 308:681–685.

Rodrigue, D. C., E. E. Mast, K. D. Greene, J. P. Davis, M. A. Hutchinson, J. G. Wells, T. J. Barrett, and P. M. Griffin. 1995. A university outbreak of *Escherichia coli* O157:H7 infections associated with roast beef and an unusually benign clinical course. J. Infect. Dis. 172:1122–1125.

Samadpour, M., J. E. Ongerth, J. Liston, N. Tran, D. Nguyen, T. S. Whittman, R. A. Wilson, and P. I. Tarr. 1994. Occurrence of Shiga-like toxin-producing *Escherichia coli* in retail fresh seafood, beef, lamb, pork, and poultry from grocery stores in Seattle, Washington. Appl. Environ. Microbiol. 60:1038–1040.

Saunders, J. R., M. J. Sergent, A. J. McCarthy, K. J. Mobbs, C. A. Hart, T. S. Marks, and R. J. Sharp. 1999. Genetics and molecular ecology of *Escherichia coli* O157. Pages 1–25 in *Escherichia coli* O157 in Farm Animals. C. S. Stewart and H. J. Flint, ed. CAB International, Wallingford, UK.

Saxena, S. K., A. D. O'Brien, and E. J. Ackerman. 1989. Shiga toxin, Shiga-like toxin II variant, and ricin are all single-site RNA N-glycosidases of 28S RNA when microinjected into Xenopus oocytes. J. Biol. Chem. 264:596–601.

Schmidt, H., B. Henkel, and H. Karch. 1997. A gene cluster related to type II secretion pathway operons of gram-negative bacteria is located on the large plasmid of enterohemorrhagic *Escherichia coli* O157 strains. FEMS Microbiol. Lett. 148:265–272.

Schurman, R. D., H. Hariharan, S. B. Heaney, and K. Rahn. 2000. Prevalence and characteristics of Shiga toxin-producing *Escherichia coli* in beef cattle slaughtered on Prince Edward Island. J. Food Prot. 63:1583–1586.

Sekla, L., D. Milley, W. Stackiw, J. Sisler, J. Drew, and D. Sargent. 1990. Verotoxin-producing *Escherichia coli* in ground beef—Manitoba. Can. Dis. Wkly. Rep. 16:103–105.

Shaw, D. J., C. Jenkins, M. C. Pearce, T. Cheasty, G. J. Gunn, G. Dougan, H. R. Smith, M. E. J. Woolhouse, and G. Frankel. 2004. Shedding patterns of verocytotoxin-producing *Escherichia coli* strains in a cohort of calves and their dams on a Scottish beef farm. Appl. Environ. Microbiol. 70:7456–7465.

Sheng, H., M. A. Davis, H. J. Knecht, D. D. Hancock, J. Van Donkersgoed, and C. J. Hovde. 2005. Characterization of a Shiga toxin-, intimin-, and enterotoxin hemolysin-producing *Escherichia coli* ONT:H25 strain commonly isolated from healthy cattle. J. Clin. Microbiol. 43:3213–3220.

Shinagawa, K., M. Kanehira, K. Omoe, I. Matsuda, D. Hu, D. A. Widiasih, and S. Sugii. 2000. Frequency of Shiga toxin-producing *Escherichia coli* in cattle at a breeding farm and at a slaughterhouse in Japan. Vet. Microbiol. 76:305–309.

Siegler, R. L., M. K. Milligan, T. H. Burningham, R. D. Christofferson, S. Y. Changand, and L. B. Jorde. 1991. Long term renal outcome and prognostic indicators in the hemolytic-uremic syndrome. J. Pediatr. 118:195–200.

Smith, D. R., J. T. Gray, R. A. Moxley, S. M. Younts-Dahl, M. P. Blackford, S. Hinkley, L. L. Hungerford, C. T. Milton, and T. J. Klopfenstein. 2004. A diagnostic strategy to determine the Shiga toxin-producing *Escherichia coli* O157 status of pens of feedlot cattle. Epidemiol. Infect. 132:297–302.

Synge, B. A., G. F. Hopkins, W. J. Reilly, and J. C. M. Sharp. 1993. Possible link between cattle and *E. coli* O157 infection in a human. Vet. Rec. 133:507.

Thran, B. H., H. S. Hussein, M. R. Hall, and S. F. Khaiboullina. 2001. Shiga toxin-producing *Escherichia coli* in beef heifers grazing an irrigated pasture. J. Food Prot. 64:1613–1616.

USDA-APHIS-VS. 1997. An update: *Escherichia coli* O157:H7 in humans and cattle. USDA Animal and Plant Health Inspection Service, Veterinary Service, Centers for Epidemiology and Animal Health, Fort Collins, CO.

Werber, D., A. Fruth, A. Liesegang, M. Littmann, U. Buchholz, R. Prager, H. Karch, T. Breuer, H. Tschape, and A. Ammon. 2002. A multistate outbreak of Shiga toxin-producing *Escherichia coli* O26:H11 infections in Germany, detected by molecular subtyping surveillance. J. Infect. Dis. 186:419–422.

Whittam, T. S., M. L. Wolfe, I. K. Wachsmuth, F. Orskov, I. Orskov, and R. A. Wilson. 1993. Clonal relationship among *Escherichia coli* strains that cause hemorrhagic colitis and infantile diarrhea. Infect. Immun. 61:1619–1629.

WHO. 1998. Zoonotic non-O157 Shiga toxin-producing *Escherichia coli* (STEC). Report of a WHO Scientific Working Group Meeting. World Health Organization, Geneva, Switzerland.

Willshaw, G. A., S. M. Scotland, and B. Rowe. 1997. Vero-cytotoxin-producing *Escherichia coli.* Pages 421–448 in *Escherichia coli:* Mechanisms of Virulence. M. Sussman, ed. Cambridge Univ. Press, Cambridge, UK.

Wilson, J. B., S. A. McEwen, R. C. Clarke, K. E. Leslie, R. A. Wilson, D. Waltner-Toews, and C. L. Gyles. 1992. Distribution and characteristics of verotoxigenic *Escherichia coli* isolated from Ontario dairy cattle. Epidemiol. Infect. 108:423–439.

Yatsuyanagi, J., S. Saito, and I. Ito. 2002. A case of hemolytic-uremic syndrome associated with Shiga toxin 2-producing *Escherichia coli* O121 infection caused by drinking water contaminated with bovine feces. Jpn. J. Infect. Dis. 55:174–176.

Zhao, T., M. P. Doyle, J. Shere, and L. Garber. 1995. Prevalence of *Escherichia coli* O157:H7 in a survey of dairy herds. Appl. Environ. Microbiol. 61:1290–1293.

Zhao, C., B. Ge, J. De Villena, R. Sudler, E. Yeh, S. Zhao, D. G. White, D. Wagner, and J. Meng. 2001. Prevalence of *Campylobacter* spp., *Escherichia coli,* and *Salmonella* serovars in retail chicken, turkey, pork, and beef from the Greater Washington, DC area. Appl. Environ. Microbiol. 67:5431–5436.

Zweifel, C., S. Schumacher, M. Blanco, J. E. Blanco, T. Tasara, J. Blanco, and R. Stephan. 2005. Phenotypic and genotypic characteristics of non-O157 Shiga toxin-producing *Escherichia coli* (STEC) from Swiss cattle. Vet. Microbiol. 105:37–45.