FOOD SAFETY

Current Status and Future Needs

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A report from

AMERICAN ACADEMY OF MICROBIOLOGY

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EXECUTIVE SUMMARY

A colloquium was convened by the American Academy of Microbiology to discuss issues relating to the safety of the food supply in the United States and to chart directions for future research. The colloquium was held in Nashville, Tennessee, August 14-16, 1998. The principal findings of the colloquium are summarized below.

There is no widely accepted definition of safe food. Food safety is evaluated relative to acceptable levels of risk. Food safety problems evolve with changes in society, economy, lifestyle, and eating habits. Many of the foodborne pathogens themselves are evolving, and new pathogens and strains are emerging that are adapted to new environmental niches. The process of improving the safety of the food supply must recognize and respond to these new challenges.

Until recently, surveillance efforts to track the incidence of foodborne disease in the United States have been uneven. Typically, more information is collected and available for epidemic outbreaks than for sporadic cases of foodborne illnesses. Estimates by the Centers for Disease Control and Prevention of the annual incidence of foodborne disease in this country range from 6.5 million to 76 million cases. Annual mortality has been estimated to be as high as 5,000 to 9,000. With the establishment of the FoodNet surveillance system in early 1996, more and better quality data are now being collected.

There is growing recognition of the importance of applying advances in the field of microbial ecology to the analysis of problems relating to food safety. The focus on particular pathogenic microorganisms is being broadened to include the normal microbiota of foods. The interactions among microbes, plants, animals, and humans must be analyzed at each step along the farm-to-table colloquium. Given the plasticity of microbial evolution, it is important to determine if particular food processing practices are exerting selective pressures for the emergence of resistant pathogenic strains.

The increasing refinement of risk assessment techniques presents new opportunities for systematically evaluating challenges to food safety and developing targeted interventions for resolving them. Risk assessment can be used to set research priorities and provide a framework for interdisciplinary efforts to improve food safety.

INTRODUCTION

Food safety is evaluated in terms of acceptable levels of risk. Given the scope and magnitude of the food supply in modern societies, there is no way to ensure that all food is kept free from potential sources of contamination. Instead, food safety is enhanced by systematically concentrating upon minimizing opportunities for contamination at every point from food production and processing to distribution, preparation, and consumption. Although previous advances, such as pasteurization and refrigeration, and contemporary improvements in hazard analysis and control have significantly improved the safety of the food supply, foodborne disease remains a major cause of morbidity and mortality. The Centers for Disease Control and Prevention (CDC) estimates that at least 6.5 million and as many as 76 million cases of foodborne disease occur in the United States each year, with 325,000 hopitalizations (Bennett, et al., 1987; CAST, 1994; Mead, et al.). Estimates of the annual number of deaths caused by foodborne disease in this country range as high as 5,000 to 9,000 (Bennett, et al., 1987; Mead, et al.). Due to differences in data collection procedures and methods of analysis, however, estimates of the annual incidence of foodborne disease vary widely. Therefore, it is more accurate to judge food safety relative to defined subpopulations, such as the immunocompromised, than for the general population as a whole.

Although previous advances . . . have significantly improved the safety of the food supply, foodborne disease remains a major cause of morbidity and mortality.

The process of ensuring the safety of the food supply is dynamic. Changes in the types of food consumed, the geographic origins of food products, and the ways in which different foods are processed affect both the potential for contamination and the adequacy of safety measures. For example, a greater reliance on prepackaged convenience foods has lowered overall consumer knowledge of safe food preparation and handling practices compared to that of previous generations. Consumers now rely more on others to ensure that the foods they consume are safe. Changes in food processing technologies and in consumer preferences have led to increased consumption of minimally processed foods and greater importation of fresh produce from other countries. These developments have contributed to the increased presence of newly emergent pathogens, such as *Cyclospora* sp. Acquisition of antibiotic resistance and/or increased virulence by strains of older pathogens also presents new challenges to ensuring the safety of the food supply. In addition, increased centralization of food processing presents new risks of larger-scale contamination events.

In earlier decades, diseases such as tuberculosis and typhoid fever were the focus of food safety concerns. Trichinosis and cholera were also more common then. Public health requirements and improvements in food processing greatly reduced the incidence of many of these foodborne illnesses. The use of thermal processes to can food and pasteurize milk significantly lessened the incidence of botulism and diseases commonly transmitted by dairy products (Foster, 1989). Today *Clostridium botulinum*, *Staphylococcus aureus*, and *Salmonella* spp. remain among the major foodborne pathogens, but during the last two decades food-borne diseases such as shigellosis, listeriosis, campylobacteriosis, and diseases caused by pathogenic strains of *Escherichia coli* have become increasingly salient. These new concerns necessitate continued investment in research and technology development to improve the safety of the food supply.

A better understanding of the genetics, physiology, and virulence of foodborne pathogens, as well as how microbes, humans, and animals interact, has provided an intellectual and technological foundation upon which new pathogen control programs and disease prevention strategies are being built. These strategies incorporate the latest developments in molecular microbiology and make use of new approaches for the diagnosis and prevention of disease. More sensitive technologies for detecting and "fingerprinting" foodborne pathogens and more highly advanced information technology systems for enhanced surveillance allow investigators to detect and trace outbreaks of foodborne illness more rapidly and accurately. Advances in risk assessment methodology now make it possible to integrate information from the various stages in the food production process. This capability can be used to identify particular steps in the food supply system for targeted intervention to control hazards and prevent disease. The challenge for the future is not only to develop improved technologies for detecting and controlling pathogens, but also to integrate more effectively the various disciplines involved in the study and control of foodborne disease.

FACTORS THAT INFLUENCE THE INCIDENCE OF FOODBORNE DISEASE

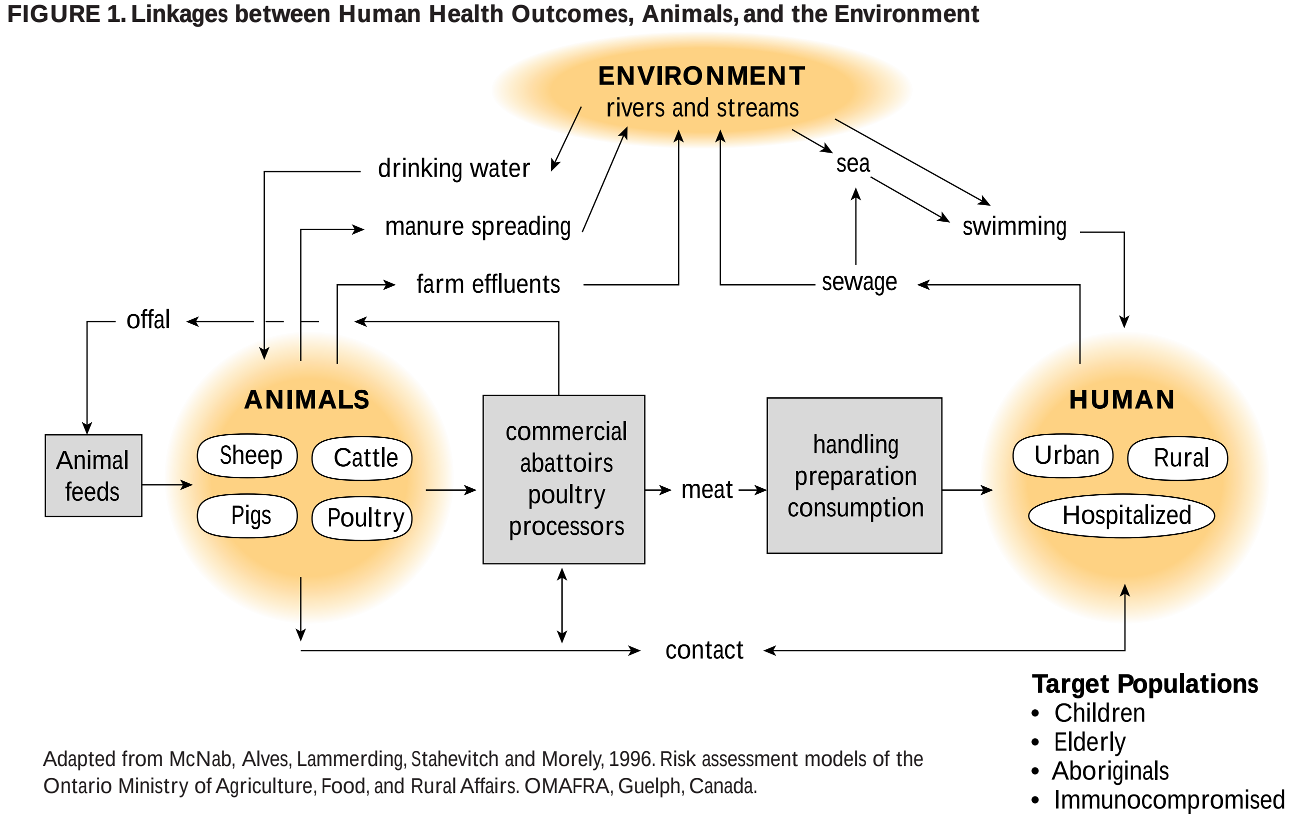
The food supply system forms a continuum from the farm to the consumer's plate. Factors that contribute to the incidence of foodborne disease may be found at every step of the way. In order to improve food safety, the entire process should be examined to determine control points at which prevention steps can be implemented. In particular, the effects of various ecological pressures on the pathogenicity of organisms need to be more clearly understood (Figure 1). More thorough study of the ecology of foodborne pathogens will allow investigators to better identify how and when food animals and produce become infected or contaminated and where pathogenic organisms are introduced in the production and processing steps. The following discussion of the factors that influence the incidence of foodborne disease is organized by stage in the food supply system. This analysis is prefaced with brief considerations of the major pathogens that cause foodborne illness and of certain characteristics of subpopulations that contribute to an increased susceptibility to disease.

Primary Foodborne Pathogens

Table 1 lists characteristics of diseases caused by the primary known foodborne pathogens. Each year, however, there are a large number of cases of food-related illnesses for which the causes are not identified. For example, the etiological agents responsible for about 50% of human diarrheal diseases in the United States are unknown (Bean and Griffin, 1990; Bean, et al., 1997). If it assumed that foodborne microorganisms are the likely cause of the majority of gastrointestinal infections, the causes of most episodes of foodborne diarrheal disease are probably not known (Fankhauser, 1998).

There are a number of reasons why it might not be possible to identify a causal pathogen from samples obtained from individuals with a disease of unknown etiology. These include the following: (i) the illness was not of infectious origin; (ii) the sample was not obtained at the appropriate time in the patient's illness; (iii) the current culture and detection methods do not include a test for a specific causal pathogen or the

FIGURE 1. Linkages between Human Health Outcomes, Animals, and the Environment



Adapted from McNab, Alves, Lammerding, Stahevitch and Morely, 1996. Risk assessment models of the Ontario Ministry of Agriculture, Food, and Rural Affairs. OMAFRA, Guelph, Canada.

TABLE 1: Characteristics of diseases caused by selected foodborne bacteria, parasites, and viruses

Name of organism (disease)	Symptoms	Onset	Duration	Target populations	Source	Sequelae
BACTERIA:						
Bacillus cereus (B. cereus food poisoning)	two distinct forms; diarrheal illness including abdominal cramps, nausea, vomiting rare emetic (vomiting) illness including nausea and vomiting	diarrheal illness 6-15 hours emetic illness 0.5-6 hours	diarrheal illness 12-24 hours emetic illness 6-24 hours	all populations susceptible	soil, dust	—
Campylobacter jejuni (Campylobacteriosis)	diarrhea (may contain blood), fever, nausea, vomiting, abdominal pain, headache, muscle pain	2-5 days	2-10 days	children <5 years, young adults 15-29	cattle, chickens, birds, flies, stream or pond water	reactive arthritis, hemolytic uremic syndrome, meningitis, Guillain-Barré Syndrome
Clostridium botulinum (botulism)	fatigue, weakness, double vision, respiratory failure	18-36 hours, varies 4 hours-8 days	months	all populations susceptible	soil, sediment, intestinal tracts of fish and mammals	—
Clostridium perfringens (perfringens food poisoning)	diarrhea, cramps, nausea, and vomiting rare	8-22 hours	<24 hours, may persist 1-2 weeks	all populations, young and elderly most affected	soil, feces	—
Enterotoxigenic *Escherichia coli* (ETEC; Travelers' diarrhea)	watery diarrhea, abdominal cramps, low grade fever, nausea, malaise	1-3 days	days	all populations susceptible	water, human sewage	—
Enteropathogenic *Escherichia coli* (EPEC; Infantile diarrhea)	watery or bloody diarrhea			infants	feces	—
Enterohemorrhagic *Escherichia coli* O157:H7 (EHEC; Hemorrhagic colitis)	severe cramping, watery diarrhea becoming bloody, low grade or absent fever	12-60 hours	2-9 days to weeks	children	cattle, deer	0-15% children develop hemolytic uremic syndrome (HUS); 50% elderly develop thrombotic thrombocytopenic purpura (TTP)
Enteroinvasive *Escherichia coli* (EIEC; Bacillary dysentery)	abdominal cramps, diarrhea containing blood and mucus, vomiting, fever, chills	12-72 hours	days to weeks	all populations susceptible	feces	hemolytic uremic syndrome (HUS)
Listeria monocytogenes (Listeriosis)	septicemia, meningoencephalitis, spontaneous abortions, stillbirths, influenza-like symptoms	few days to 6 weeks	days to weeks	pregnant women/ fetus, immunocom-promised persons, cancer and AIDS patients, and those with chronic diseases, elderly, antacid or cimetidine users	soil, improperly made silage	—
Salmonella species (salmonellosis)	nausea, chills, vomiting, cramps, fever, headache, diarrhea, dehydration	6-48 hours	1-4 days	all populations susceptible, but more severe symptoms in infants, elderly, infirm, AIDS patients	water, soil, insects, animal feces, raw meats, raw poultry, raw seafoods	2-3% of population; reactive arthritis 3-4 weeks after onset of symptoms
Shigella species (Shigellosis)	abdominal pain, diarrhea, fever, vomiting, sometimes cramps, nausea	1-7 days	4-7 days	infants, elderly, infirm, AIDS patients		2-3 percent of population; mucosal ulceration, rectal bleeding, reactive arthritis, hemolytic uremic syndrome
Staphylococcus aureus (Staphylococcal food poisoning)	nausea, vomiting, cramps, diarrhea, prostration	1-6 hours	1-2 days	all populations susceptible	air, dust, sewage, water, milk, food equipment, humans, animals, nasal passages and throats hair, skin, boils	—

Suspect foods	Infective dose	Fatality rate
diarrheal illness: meats, milk, vegetables, fish, soups emetic illness: rice products, potatoes, pasta, cheese products	diarrheal illness >1,000,000	rare
raw chicken, turkey, raw milk, beef, pork, lamb, shellfish, water	400-500 bacteria	0.001%
canned foods, smoked and salted fish, chopped bottled garlic, sautéed onions, honey	small amount of toxin	7.5%
meats, meat products, poultry, gravy	>1,000,000	<0.1%
dairy products	>1,000,000 organisms	<0.1%
raw beef and chicken	low levels in infants, >1,000,000 organisms in adults	<0.1%; 50% mortality in developing countries
undercooked or raw hamburger, raw milk, unpasteurized apple cider	10-100 organisms	2%
hamburger, unpasteurized milk	10 organisms to 100,000,000 organisms in adults	<0.1%
raw milk, soft-ripened cheeses, ice cream, raw vegetables, fermented raw-meat sausages, hot dogs, luncheon meats, raw and cooked poultry, raw and smoked fish	unknown but probably <1000 organisms	as high as 70%
raw meats, poultry, eggs, milk, dairy products, fish, shrimp, frog legs, yeast, coconut, sauces and salad dressings, cake mixes, cream-filled desserts and topping, dried gelatin, peanut butter, cocoa, chocolate	as few as 15-20 cells; depends upon age and health of host; strain differences	1% of population; 15% in elderly
salads (potato, tuna, shrimp, macaroni, and chicken), raw vegetables, milk and dairy products, poultry	as few as 10 cells	10-15%
meat and meat products, poultry and poultry products, salads (egg, tuna, chicken, potato, macaroni), cream-filled pastries, cream pies, milk and dairy products	<1.0 μg toxin produced when cell levels exceed 100,000 organisms/gram	0.02%

continued

pathogen is a virus that is not detected by current methods; and (iv) the causal microorganism is a little understood or newly emergent pathogen. Existing epidemiological and surveillance activities should be expanded and new ones developed to determine the unknown causes of existing foodborne diseases and to identify new foodborne pathogens.

At-Risk Subpopulations

Health and age characteristics that contribute to increased susceptibility to disease are important factors respective to disease incidence in the population as a whole. The newly defined subpopulations at risk for foodborne illnesses include an age-related group (individuals under 5 or over 50 to 60 years of age), an immunocompromised group (individuals receiving anticarcinogenic or immunosuppressive drug or antibiotic therapies or who have received organ transplants), and a group comprising chronic disease patients (e.g., individuals with diabetes or asthma or with heart, liver, or intestinal diseases). These groups constitute as much as 10 to 20% of the population (CAST, 1994). Other at-risk groups include pregnant women and AIDS patients.

The minimal level of immunological impairment needed to increase susceptibility to foodborne disease is not known. Factors contributing to increased susceptibility range from identifiable immunological disorders to minor medical or dietary conditions. Examples of the latter include hemochromatosis or high consumption of dietary iron (leads to excessive iron levels in the blood), excessive use of antacids (increases the pH in the stomach), consumption of large volumes of liquid (dilutes stomach acids and promotes rapid transit of pathogens), and ingestion of fatty foods (protects pathogens against stomach acids) (CAST, 1994).

Food Supply System

Among the manifold processes constituting the food supply system there are numerous practices that contribute to the incidence of foodborne disease. Primarily, these practices have to do with the creation or persistence of situations that increase the likelihood of microbial contamination at levels high enough to cause disease. Common examples include improper disposal of manure on the farm, use of contaminated water to wash produce, and inadequate refrigeration of food products.

Preslaughter practices. Healthy herd management includes providing adequate housing and nutrition, ensuring appropriate veterinary care, and properly disposing of manure. Certain features of modern food animal and aquaculture production, such as the increase in population densities at which

TABLE 1, continued

Name of organism (disease)	Symptoms	Onset	Duration	Target populations	Source	Sequelae
BACTERIA:						
Vibrio cholerae Serogroup 01 (Cholera)	mild, watery diarrhea, abdominal cramps, nausea, vomiting, dehydration, shock	6 hours-5 days	days	all populations but especially immunocompromised individuals, reduced gastric acidity, malnutrition	raw shellfish, water, poor sanitation	—
Vibrio cholerae Serogroup Non-01 (Non 01 *V. cholerae* gastroenteritis)	diarrhea, abdominal cramps, fever, some vomiting and nausea	1-3 days	diarrhea lasts 6-7 days	all populations susceptible	coastal waters, raw oysters	septicemia
Vibrio parhaemolyticus (*V. parahaemolyticus* gastroenteritis)	diarrhea, abdominal cramps, nausea, vomiting, headache, fever, chills	4-96 hours, average 15 hours	4-7 days	all populations susceptible	coastal and estuarine waters, raw shellfish	septicemia
Vibrio vulnificus	wound infections, gastroenteritis, primary septicemia	16 hours	days to weeks	all populations susceptible, especially those with chronic illness, AIDS patients	coastal waters, sediment, plankton, shellfish	—
Yersinia enterocolitica (Yersiniosis)	diarrhea and/or vomiting, fever, abdominal pain; symptoms mimic appendicitis	1-3 days	2-3 weeks	very young, debilitated, very old, persons taking immunosuppressive therapy	swine, birds, beavers, cats, dogs, ponds, soil, pigs, squirrels	unnecessary appendectomies, reactive arthritis in 2-3% of cases, Graves Disease, Reiter's Syndrome
PARASITES:						
Cryptosporidium parvum (Cryptosporidiosis)	severe watery diarrhea, sometimes fever, nausea, vomiting	1-2 weeks	2-4 days up to 1-4 weeks		incidence high in day-care centers	—
Cyclospora cayetanensis (Cyclosporiasis)	watery diarrhea, weight loss, bloating, nausea, vomiting, low grade fever	1-11 days	days to weeks	all populations susceptible	water	—
Giardia lamblia (Giardiasis)	diarrhea, cramps, bloating	5-24 days	weeks to years	all populations susceptible, more frequent in children	dogs, cats, beavers, bears, feces	—
Toxoplasma gondii (Toxoplasmosis)	resembles mononucleosis	10-23 days	varies	pregnant women, AIDS patients more susceptible	sheep, pigs, bear, oocysts in cat feces	—
Trichinella spiralis	—	—				
VIRUSES:						
Hepatitis A Virus	sudden onset of fever, malaise, nausea, anorexia, abdominal discomfort, followed by jaundice	1-7 weeks, average 30 days, communicable until 1 week after appearance of jaundice	1-2 weeks for mild cases to months	all populations susceptible, more common in adults than children	infected workers, feces	chronic fatigue
Norwalk and Norwalk-like Viruses	nausea, vomiting, diarrhea, abdominal pain, headache and low grade fever	1-2 days	1-6 days		feces	—
Rotavirus (Infantile diarrhea)	vomiting, watery diarrhea (4-8 days), low grade fever	1-3 days	4-6 days	all populations susceptible, particularly premature infants, children 6 months-2 years, elderly, immunocompromised	infected hands, objects, utensils	

Suspect foods	Infective dose	Fatality rate
seafood, water	1,000,000 bacteria	<1.0%
shellfish	>1,000,000	<1.0%
fish and shellfish	>1,000,000 bacteria	<1.0%
oysters, clams, crabs	unknown in healthy individuals, but pre-disposed persons <100 organisms	55% for septicemia patients, 24% for wound infections, >50% for patients with chronic illnesses
pork, beef, lamb, ice cream, raw milk, tofu, water	unknown	0.03%
contaminated water, fish	<30 organisms	—
raspberries	—	—
contaminated water, ice	1 or more cysts	—
raw or undercooked pork, or mutton, rarely beef, bear	—	—
undercooked pork, game, bear, walrus	1-500 larvae	
cold cuts, sandwiches, fruits, fruit juices, milk, milk products, vegetables, salads, shellfish, iced drinks, water, raw shellfish, salads	10-100 virus particles	<0.4%
ice, water, including municipal supplies, wells, lakes, swimming pools; shellfish, salad ingredients, raw clams and oysters	—	unknown but presumed low
water	10-100 virus particles	100 cases/year

Adapted from Cast, 1994; Knabel, 1995; Hui, et al., 1994.

cattle, poultry, and fish are raised, may increase the risk of microbial contamination. The close proximity of numerous animals increases the likelihood that microbes will be transmitted from one animal to another. This applies not just to microbes that cause disease in animals but also to bacteria, such as *Salmonella* spp., *Escherichia coli* O157:H7, and *Campylobacter* spp., which reside in the intestinal tracks of livestock without causing disease. Manure from animals colonized with *E. coli* O157:H7 can contaminate the external hide or feed of noncolonized animals and thus cross-contaminate other animals or food products.

Poor farm management practices have been implicated in the spread of human pathogens that are transmitted via fecal contamination. Water supplies contaminated by animal or human feces can spread potential human pathogens among exposed animals and on plant products. The use of untreated human waste as sludge for fertilizer can introduce pathogens that are normally associated primarily with humans, such as *Cyclospora* spp., into the intestines of animals. More research on animal environments and pathogen interactions is needed to improve procedures and control programs to reduce pathogen incidence at the farm level.

Antimicrobial compounds are routinely used in animal husbandry. However, by altering the composition of the microbiota of these animals, this large-scale prophylactic use of antibiotics may be linked to adverse effects on human health. There may be increased shedding of human pathogens by these animals, and development of antibiotic-resistant pathogens may be enhanced. Presently, in large outbreaks of salmonellosis, at-risk individuals may develop a systemic form of the disease that can be fatal and which must be treated by antibiotics. Emergence of the multidrug-resistant strain Salmonella Typhimurium Definitive Type 104 (DT104) has raised concerns about possible further development of resistant foodborne pathogens (Tauxe, 1991). Instances of other antibiotic-resistant pathogen isolations have also been documented.

Wild and domestic animals in the farm environment can serve as vectors and reservoirs for disease-causing organisms. Some examples include the role of domestic cats and birds in the transmission of *S. typhimurium* DT104 and *Toxoplasma gondii* (Frenkel, 1990; Low, et al., 1996; Wall, et al., 1996), the role of rats in the transmission of trichinosis to swine (Leiby, et al., 1998), and the role of deer, cattle, sheep, and birds in the spread of *E. coli* O157:H7 (Chapman and Ackroyd, 1997; Keene, et al., 1997; Kudva, et al., 1996; Pierard, et al., 1997; Rice, 1995). Our understanding of these transmissions is not yet sufficient to develop effective control measures. The introduction into the food supply of animal species previously classified as exotic, such as emus and ostriches, may provide new opportunities for *Salmonella* spp. or other pathogens. We have little information about how the domestication process may affect the susceptibility of various animals to disease or to colonization by novel human pathogens.

Preharvest practices. A similar picture emerges when the environment of produce farms is examined. High-density cultivation increases the possibility of transmission of human pathogens that can survive on the surface of plants. Genetic manipulation of plants may also affect the potential of plants and their products to carry human pathogens. Use of uncomposted animal manure or human waste for fertilizers and use of water contaminated with human or animal feces introduce opportunities for contamination of plants. Contamination of some fresh produce, such as sprouts or apple cider, is potentially more serious than contamination of animal products because these foods may be more likely to be consumed without processing treatments that would kill pathogenic microbes (Tauxe, et al., 1997). A potential health problem specific to plants is the ability of plants and seeds to support the growth of fungi that produce aflatoxin or other mycotoxins.

The slaughtering process. The slaughtering process can lead to contamination of carcasses by organisms derived from the animal's intestinal tract or its external hide. Such contamination can occur at more than one stage in the process. For example, prior to slaughter animals are often transported to the slaughterhouse under conditions that not only increase the likelihood of pathogen transmission but also make the animals more susceptible to stress-induced reactions such as increased fecal shedding of organisms. Additionally, the impact of the fasting of animals on their microbiota before and during transport to the processing plant is not well understood. Because of the difficulty in decontaminating crates and trucks used to ship animals, pathogens from one shipment of animals may contaminate succeeding shipments.

At the slaughterhouse, microbes from hides and feces can contaminate not only the meat from those animals but the equipment and environment as well, leading to cross-contamination of meat from animals slaughtered subsequently (Gill, 1998; Sofos, 1994; Sofos and Smith, 1998). Contamination can also occur by workers who are infected with foodborne pathogens and who handle animal carcasses. Other critical factors that may influence the numbers of microbes contaminating the meat are the length of time the meat is held and the temperature at which it is stored.

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Harvesting practices. Pickers can contaminate plants or plant products during and after harvest. Washing fruits and vegetables with water contaminated with animal or human feces and storing produce on ice made from contaminated water are well-established routes of contamination. As with meat handling, cross-contamination during storage and handling can provide further opportunities for the multiplication of microbes.

Aquaculture. Aquaculture has gained acceptance as a commercially viable way of producing high-quality fish, shellfish, and mollusks and accounts for 15% of the U.S. seafood supply. Imported seafood, much of which is also produced in aquaculture, now accounts for more than 50% of our per capita consumption of seafood. Although aquaculturally produced seafood is relatively safe, certain products do present significant health risks. Generally, the microbiota of seafood reflects that of the aquatic environment at the time of its capture or harvest, and appropriate attention needs to be paid to this. Finfish or shellfish harvested from inshore water contaminated by human or animal feces may contain pathogenic microorganisms. Certain viruses, such as hepatitis A and Norwalk, are being increasingly implicated in illnesses caused by seafood consumption. The same is true for the bacterial pathogens *Clostridium botulinum* type E, *Staphylococcus aureus*, *Salmonella* spp., *Yersinia* spp., *Listeria monocytogenes*, *Vibrio parahaemolyticus*, and *Vibrio vulnificus* (Ahmed, 1991; Garrett, et al., 1997).

Consumption of raw seafood, particularly members of the mollusk family, poses a well-known risk for food poisoning. Chemical toxins, such as those responsible for paralytic shellfish poisoning, diarrhetic shellfish poisoning, and amnesic shellfish poisoning, also present serious dangers to the consumer which may not be easily avoidable. The toxigenic algae responsible for making some of these toxins are consumed by finfish or shellfish and may be associated with specific locales. These toxins are heat resistant and are not inactivated by cooking. Bacterial spoilage of fish after harvest can result in the high histamine levels that cause scombroid poisoning. Heavy metal contamination of seafood products, due to high levels of mercury or other compounds in the water, has also been demonstrated.

Food processing. Several enteric pathogens have been shown to have the ability to survive at low pH (Gorden and Small, 1993), and acidic foods have been implicated in several outbreaks of salmonellosis and *E. coli* O157:H7 infection (Feng, 1995). Food processing can induce bacterial stress responses that may increase pathogen virulence. Acid stress may make bacteria better able to survive the acidity of the stomach, allowing entry into the small intestine where they can cause adverse health effects. Sublethal temperature and salt stresses may be enhanced by different processing techniques and can increase a foodborne pathogen's resistance to high temperature and to high salt concentration. A number of these stress responses seem to be linked. Temperature stress (both low and high) can influence the acid tolerance response and induce resistance to certain disinfectants and antibiotics. Thus, exposure to one stress may increase the ability of microbes to respond more effectively to other subsequent stresses and make them better able to survive common food preservation procedures and host barriers to infection (Archer, 1996).

Processing treatments may not necessarily be selective against pathogens but might eliminate other microorganisms in the ecologically diverse population that might otherwise act to prevent the pathogens from growing. Thus, the ecological balance may shift, creating an entirely new population dynamic with potentially adverse human health effects. Antimicrobial agents used in food processing can also alter the microbiota of the food, resulting in a different ecology of the final product.

Before advances in transportation, a processing plant obtained raw materials almost solely from a relatively small surrounding geographic area, and the processed products were rapidly distributed to local markets. These factors limited the range of recall efforts in cases of contamination. Today, the centralization of food processing facilities has resulted in a much wider distribution of food products which, if the latter are contaminated, can have a much greater impact on public health. Other changes, such as new product development or reformulation of existing food products, may result in products having increased susceptibility to contamination by foodborne pathogens. For example, an outbreak of botulism in hazelnut-flavored yogurt in the United Kingdom has been traced to the use of aspartame in place of sugar. This change created a new niche for the pathogenic organism, *C. botulinum* (O'Mahoney, et al., 1990).

Preparation and consumption of food in the home. Much is known about hazards associated with consumption of undercooked and improperly cleaned food and about the potential for cross-contamination of foods on cutting boards and food preparation counter surfaces. By comparison, relatively little is known about disease ecology in the home, especially concerning the spread of disease-causing organisms. The spread of salmonella from the hands of a food preparer to other individuals is poorly understood. Other contaminated surfaces, such as faucets, floors, sponges, and dishtowels, could provide similar avenues for transmission of disease (Knabel, 1995). The contribution of inadequate refrigeration temperatures to the spread of foodborne disease is well known in the food and restaurant businesses but is not well understood by consumers. Educated guesses can be made about these problems, but there is little hard evidence upon which to draw conclusions and take corrective action.

Areas of Future Research

Continued research in microbial ecology and adaptation is essential for improving our understanding of the factors implicated in the incidence of foodborne disease. The complex interactions between microorganisms and their environment need to be better understood at every stage of the food supply process. While knowledge of the microbial ecology in environmental settings such as water and soil has already entered a new era, characterized by rapid advances in understanding microbial diversity and microbial interactions, no comparable movement has occurred within environmental food microbiology. In fact, traditional thinking in this area has focused on the ecology of individual microbes, and, to a limited extent, on their interaction with the human, animal, or plant host. The study of how microbes interact with each other, with the environment, and with animals and plants at various stages of the field-to-table progression of the food chain has been largely neglected.

There are numerous specific issues, ranging from the evolution of particular pathogens to processes of competitive exclusion and the adherence of bacteria to foods, which need to be addressed. Progress in these areas should lead to the design of more effective intervention measures. A brief consideration of some of the more important questions to be resolved is summarized below.

For all foodborne pathogens, more needs to be learned about host factors that promote or discourage colonization. These factors include the immune response as well as nutritional interactions between the host and the pathogen and between the pathogen and other microbes in the same niche. Much of the available information about host-pathogen interaction has focused on evasion or subversion of the immune system. No comparable body of information is available about colonization factors that are critical for the maintenance and spread of foodborne pathogens between animals and humans. A better understanding of colonization processes will aid efforts to develop competitive exclusion strategies using beneficial or innocuous bacteria to outcompete pathogens for niches in the intestinal tract of food animals.

The evolution of *E. coli* O157:H7 and how it is stably maintained in the rumen, how it establishes a niche, and why it makes a toxin are not well understood. The mechanisms by which some known parasitic pathogens, such as *Cryptosporidium* sp. and *Cyclospora* sp., cause disease have not yet been studied in depth. Methods for cultivating and isolating these pathogens need to be developed, and studies of their virulence factors and strategies for survival in the niches they favor need to be undertaken. The distribution and spread of common pathogens such as *Salmonella* sp. and *L. monocytogenes* in their environmental reservoir needs to be studied in greater detail. Study of the evolution of pathogens needs to be expanded to include more bacteria and other organisms, such as some of the fungi and protozoa which have become potential food safety concerns in recent years (LeClerc, 1996).

Bacterial stress responses and their implications for food safety need to be studied in real world situations where microbes in animals, plants, or foods are stressed. Considerable progress has been made toward understanding bacterial stress responses at the molecular level. This information has yet to be applied to food manufacturing practices to prevent processing from making the bacteria that remain on food more dangerous than they were when they arrived in the processing plant. Although there have been numerous studies of the mechanisms of attachment of bacteria to human and animal cells, virtually nothing is known about the attachment of bacteria to foods and food contact surfaces. A better understanding of microbial attachment is especially important for foods that are consumed raw because microbes that adhere so strongly that they are not readily removed by washing are the ones that are most likely to cause disease.

Although knowledge of antibiotic resistance mechanisms in bacteria and protozoa is well established, the mechanisms for transfer of resistance genes and frequency of transfer in the animal intestinal environment and food production processes are unknown. More needs to be learned about conditions that induce the expression of resistance genes, stimulate frequency of gene transfer, and enhance stability of resistance genes in the absence of direct antibiotic selection. Models have been developed to predict how certain foodborne pathogens respond to changes in growth parameters, including nutrients, salt, moisture, temperature, atmosphere, and chemical inhibitors. Additional studies are needed to model the interactions of pathogenic organisms with benign background microbiota. Models also need to be developed to analyze the influence of processing parameters on microbial control and food safety.

Finally, it is virtually certain that there are important foodborne pathogens that remain to be discovered. Microbiologists have developed molecular methods that provide clues to the identity of microbes that are viable but nonculturable (Balter, 1998; Pommepuy, 1996). Elucidation of such clues will help in the development of cultivation strategies and the design of detection systems. Also, epidemiological studies that include outbreak investigations and case control studies of sporadic disease can be used to identify which foods are most likely to develop foodborne disease (Bryan, et al., 1997; Todd, 1989).

SAMPLING AND SURVEILLANCE

Technological improvements in testing procedures have produced more rapid and sophisticated means of detecting certain microorganisms or their toxins at increasingly lower levels. However, development of proper sampling procedures for testing microbial contamination in food has proved to be more difficult. This problem is especially critical since for some pathogens the dose capable of causing illness is 100 organisms or less (CAST, 1994).

Especially in the raw state, foods generally contain large populations of microbiota that are not a health risk but whose physical presence often interferes with the detection of specific pathogens. In addition, most foods undergo some type of processing—i.e., heating, freezing, chilling, dehydration, or chemical treatment—which may stress the microbial population. These processes can affect the dynamics of the growth and development of microbial populations in foods as well as cause injury to bacterial cells. Unless the stressed microorganisms are allowed to recover, they are generally difficult to detect. Organisms may be present in a particular food matrix in a viable but nonculturable state, and, as such, they are likely to be "underrepresented" in tests to quantify their presence in a sample. Oftentimes, this leads to qualitative results in which only the presence or absence of a pathogen can be confirmed. This is an important drawback when trying to determine the infective dose of a particular pathogen in an outbreak situation or to quantify the effectiveness of various preservation treatments.

In addition to resolving these difficulties with sampling, there is a pressing need to standardize testing procedures to ensure that results obtained from different laboratories are comparable. Procedures to control contamination in meat, poultry, and fish have improved, but critical control points for other food processing methods need to be established. Existing surveillance programs also should be expanded to gather more complete data on epidemic outbreaks and sporadic cases of foodborne disease. Each of these issues is discussed below.

Sampling

Selection and application of appropriate sampling procedures for specific food safety concerns remains controversial. The food industry and government agencies use end-product analysis, in accordance with appropriate and accepted testing methods, to test for microbial contamination in food. However, since pathogens are not uniformly distributed in foods, it is critical that statistically sound sampling plans are devised before sampling and testing foods. But even with the best sampling plans and using the most sensitive testing methods, it cannot be determined that the analyzed sample or product lot is free of the target pathogens. To infer that the rest of the lot of food is free of pathogens is merely an assumption that is inadequate to ensure food safety.

Standardization of sampling procedures. National standardization of sampling procedures and the methods used for process validation, monitoring, and verification is badly needed. Testing methodologies and ways of reporting results must be integrated across users in the areas of agriculture, human health, and environmental monitoring if epidemiological data obtained from different steps in the farm-to-table progression are to be comparable and useful. Because the current international patchwork of different sampling protocols makes it virtually impossible to compare results from different countries, international standardization of sampling procedures would be helpful for resolving disputes over health issues and the import and export of foods from different countries.

HACCP

Since January 1998, the largest meat and poultry processing plants in the United States have been required by the U.S. Department of Agriculture (USDA) to implement a Hazard Analysis Critical Control Point (HACCP) system to control contamination in their plants. The principles of the HACCP system are outlined in Table 2. The HACCP concept dates back to collaborative efforts in the 1960s

TABLE 2:
The Seven Principles of Hazard Analysis Critical Control Points (HACCP)[1]

1. Conduct a hazard analysis. Prepare a list of steps in the process where significant hazards occur and describe the preventative measures.
2. Determine the Critical Control Points (CCP) in the process.
3. Establish the critical limits for preventative measures associated with each identified CCP.
4. Establish CCP monitoring requirements. Establish procedures for using the results of monitoring to adjust the process and maintain control.
5. Establish corrective action to be taken when monitoring indicates that there is a deviation from an established critical limit.
6. Establish procedures for verification that the HACCP system is working correctly.
7. Establish effective record-keeping procedures that document the HACCP system.

[1] Adapted from the National Advisory Committee on Microbiological Criteria for Food (1992, 1998a).

 National Advisory Committee on Microbiological Criteria for Foods, 1998a. Hazard analysis and critical control point principles and application guidelines. *J. Food Prot.* 61:672–725.

among The Pillsbury Company, the National Aeronautics and Space Administration (NASA), and the U.S. Army Research Laboratory. The program has a three-year phase-in with smaller processing plants beginning implementation in 1999 and the smallest plants adopting the system in 2000. There is a "HACCP-like" system for the seafood industry that is overseen by the FDA.

The HACCP system marks a departure from the traditional end-point analysis orientation of previous food safety systems. Instead of trying to detect microbial contamination in food products at the end of the production process, the goal of a HACCP program is to minimize contamination by establishing control procedures at certain critical points during food processing. Depending on the procedures used to process different foods, hazard points for the entry of microbial contamination are identified, and critical controls are developed. Implementation of these controls, e.g., the time that food products are held at a certain temperature, is then monitored to ensure that contamination is controlled.

Identification of definitive critical control points, however, is difficult for many of the procedures used by the food processing industry. Implementation of effective HACCP programs can be complex and slow. Extensive personnel training and careful assessment of processing conditions are required to ensure that established processes are adequate and effective in controlling microbial contamination. Some HACCP programs lack sufficient monitoring methods to ensure that the critical points in the process are under control. For those cases, testing methods need to provide "real-time" results to alert the processor of any breakdowns in sanitation or process control.

Surveillance

Table 3 presents data on the numbers and percentage totals of foodborne disease outbreaks and sporadic cases for selected years. Given the disparate nature of data collection procedures, reporting requirements, and analytical methods used in previous surveillance studies, it is difficult to determine whether the incidence of foodborne disease is increasing or decreasing. This uncertainty is due in part to improvements in the technical methods being used and to the likelihood that apparent increases in incidence are in some respect artifacts of contemporary focus. In select areas of intensive surveillance, more of the outbreaks being detected can be traced to particular food vehicles. But it is still difficult to determine rates of sporadic disease occurrence and to identify the particular food vehicles involved. Recent surveillance programs developed by the federal government in cooperation with state agencies are now beginning to provide better data with which to address some of these issues.

FoodNet. The USDA Food Safety and Inspection Service (FSIS), in conjunction with the Food and Drug Administration (FDA) and the CDC, has been collecting information since early 1996 on the incidence of foodborne disease in the United States. Originally known as the Sentinel Site Study, but now termed FoodNet, these agencies developed direct links with state and local health departments in the states of Minnesota, Oregon, and Connecticut as well as selected counties in California, Georgia, Maryland, and New York. Currently 20.3 million persons, representing 7.5% of the U.S. population, are included in the FoodNet surveillance system. Data regarding diseases linked to several of the major foodborne pathogens are collected through this program and are forwarded weekly to the CDC (CDC, 1998a). The objectives of FoodNet are (i)

TABLE 3:
Number and percentage of foodborne disease outbreaks and cases by known etiology, by etiologic agent, 1973–1987 (Bean and Griffin, 1990) and 1988–1992 (Bean, et al., 1997).

	Outbreaks (1973–1987)		Cases (1973–1987)		Outbreaks (1988–1992)		Cases (1988–1992)	
Etiologic agent	**Number**	**Percent**	**Number**	**Percent**	**Number**	**Percent**	**Number**	**Percent**
BACTERIAL								
Bacillus cereus	58	2	1123	1	21	2	433	1
Brucella	4	<1	43	<1	—	—	—	—
Campylobacter	53	2	1547	1	28	3	735	2
Clostridium botulinum	231	8	494	<1	60	6	133	<1
Clostridium perfringens	190	7	12234	10	40	4	3801	10
Escherichia coli	10	<1	1187	1	11	1	244	<1
Listeria monocytogenes	—	—	—	—	1	<1	2	<1
Salmonella	790	28	55684	45	549	55	21177	57
Shigella	104	4	14399	12	25	3	4788	13
Staphylococcus aureus	367	13	17248	14	50	5	1678	5
Streptococcus, group A	12	<1	1917	2	2	<1	135	<1
Streptococcus, other	7	<1	248	<1	—	—	—	—
Vibrio cholerae	6	<1	916	1	4	<1	34	<1
Vibrio cholerae, non-01	2	<1	11	<1	—	—	—	—
Vibrio parahaemolyticus	23	1	535	<1	4	<1	21	<1
Yersinia enterocolitica	5	<1	767	1	1	<1	2	<1
Other bacterial	7	<1	373	<1	—	—	—	—
Total bacterial	1869	66	108726	87	796	79	33183	90
VIRAL								
Hepatitis A	110	4	3133	3	43	4	2109	6
Norwalk virus	15	1	6474	5	2	<1	292	<1
Other viral	10	<1	1023	1	—	—	—	—
Total viral	135	5	10630	9	45	5	2401	7
PARASITIC								
Giardia	5	<1	131	<1	7	<1	184	<1
Trichinella spiralis	128	5	843	1	10	1	195	<1
Other parasitic	7	<1	30	<1	—	—	—	—
Total parasitic	140	5	1004	1	17	2	379	1
CHEMICAL								
Ciguatoxin	234	8	1052	1	42	4	176	<1
Heavy metals	46	2	753	1	3	<1	26	<1
Monosodium glutamate	18	1	58	<1	—	—	—	—
Mushroom poisoning	61	2	169	<1	5	<1	18	<1
Paralytic shellfish poisoning	21	1	160	<1	5	<1	65	<1
Histamine (scromboid) fish poisoning	202	7	1216	1	76	8	514	1
Other chemical	115	4	1046	1	12	1	128	<1
Total chemical	697	25	4454	4	143	14	927	2
TOTAL	**2841**	**100**	**124814**	**100**	**1001**	**100**	**36890**	**100**

An outbreak is defined as an incident in which two or more persons experience a similar illness after ingestion of a common food. For botulism and chemical poisoning, one case constitutes an outbreak.
Outbreaks of known etiology are those for which the agent laboratory evidence of a specific agent is obtained and specified criteria are met.
Outbreaks of unknown etiology are those for which adequate laboratory evidence of the etiological agent is not obtained.

to describe the epidemiology of infectious foodborne diseases of national importance, including those caused by *Campylobacter* sp., *E. coli* O157:H7, *L. monocytogenes, Salmonella* sp., *Shigella* sp., *Vibrio* sp., *Yersinia* sp., *Cryptosporidium* sp., and *Cyclospora cayetanensis*, (ii) to determine more precisely the frequency and severity of foodborne diseases in the United States, (iii) to determine the proportions of certain infections which are accounted for by the consumption of specific foods, and (iv) to assess whether federal intervention strategies are affecting the incidence of foodborne illness.

Based on FoodNet data to date, 360 million cases of diarrheal illness occur each year, resulting in ~28 million medical consultations. Additional studies will be conducted to evaluate the cause and impact of these illnesses and determine what proportion of them may be related to the consumption of contaminated foods. Individual cases of *Campylobacter* infections have been frequently diagnosed, although large outbreaks have been rare. The FoodNet surveillance system is credited with limiting the health risk to the public posed by an outbreak in the northwestern United States of *V. parahaemolyticus* associated with eating raw oysters. This suggests that foodborne illness can be addressed effectively when the appropriate authorities are provided with accurate data (CDC, 1998b, 1998c).

According to FoodNet data for 1996 and 1997, the incidence of listeriosis and typhoid fever is declining, while illnesses due to *S. enteritidis* and *S. typhimurium* DT104 are increasing. Overall, the incidence of foodborne salmonellosis in the United States seems to have plateaued. With the increased importation of food, a wider range of food vehicles is being associated with outbreaks and sporadic cases of foodborne illness. But since the FDA inspects only about 3% of imported foods (FDA, 1992), there is insufficient baseline data to estimate the effects of increasing food imports on the incidence of foodborne disease in this country.

(ii) PulseNet. A national network of state public health laboratories that perform DNA fingerprinting of bacteria isolated from patients and contaminated food was developed in 1997 as part of the National Food Safety Initiative, a joint effort by the FDA, the USDA, the CDC, and other agencies to track foodborne illnesses nationwide. This network, called PulseNet, allows comparisons of molecular fingerprint patterns through an electronic database at CDC. In this manner, seemingly unrelated outbreaks may be linked through a common microorganism. This electronic communication can be linked with disease surveillance to improve the safety of the food supply (Binder and Levitt, 1998). Continued and widened surveillance is critical for determining the overall burden of disease, evaluating risk management strategies, and detecting new problems, such as novel pathogens, risk factors, and routes of exposure.

Although methods for detecting viruses and parasites in foods are particularly lacking, the pace of advancement in improving microbiological tests for food contamination is generally regarded as being satisfactory.

Areas of Future Research

Continued improvements are needed in sampling procedures and diagnostic testing. Sampling strategies should be standardized to account for lot size and heterogeneity of pathogen distribution in foods. Although methods for detecting viruses and parasites in foods are particularly lacking (Fankhauser, et al., 1998), the pace of advancement in improving microbiological tests for food contamination is generally regarded as being satisfactory. For regulatory and legal reasons, live cultures are needed for confirmation of results and for epidemiological or trace-back investigations. Cultural enrichment of samples to detect pathogens often means that tests take at least one to two days before results are available. However, molecular techniques are being developed that provide timely information with excellent concurrence to that of traditional methods without the need to isolate a live culture.

With recent refinement of genome-sequencing technology, the genomes of selected strains of foodborne pathogens should be sequenced. Research is currently under way to determine the genome sequences of *S. typhimurium*, *Salmonella typhi*, *E. coli* O157:H7, *Shigella flexneri*, enteropathogenic *E. coli*, enterotoxigenic *E. coli*, and *Campylobacter* sp. Genome sequences need to be determined for *Yersinia enterocolitica* and *L. monocytogenes*. Insights into the virulence and infectivity of *E. coli* O157:H7 could be obtained by comparing its sequence with those for the enteropathogenic *E. coli* strains from which it is thought to be derived.

RISK ASSESSMENT

Despite the best efforts of scientists, food producers, food processors, food technologists, regulators, health care professionals, and consumers, food will inevitably carry with it some risks associated with foodborne disease. Risk analysis is being increasingly used as a formalized approach to understanding and controlling these risks (Figure 2). Risk analysis comprises three components: assessment, management, and communication (NACMCF, 1998). The information generated in conducting a risk assessment is subsequently used in the risk management and risk communication stages of risk analysis. Risk assessment is the predominant component in the application of risk analysis to issues of food safety at present.

Risk assessment is an effective means for establishing relative risks of human disease, for discovering knowledge and data gaps that limit effective risk analysis, and for providing information to develop public policies on food safety risk management. The components of risk assessment are (i) hazard identification (identification of the biological, chemical, or physical agent, disease, or adverse health outcome), (ii) exposure assessment (determination of the frequency of disease, the number of people exposed to contaminated food, and the prevalence, growth, contamination, survival, or destruction of pathogens in foods), (iii) hazard characterization (identification of the adverse health effects associated with the hazard), and (iv) risk characterization (estimation of the risk and the numbers of cases and severity of the outcome).

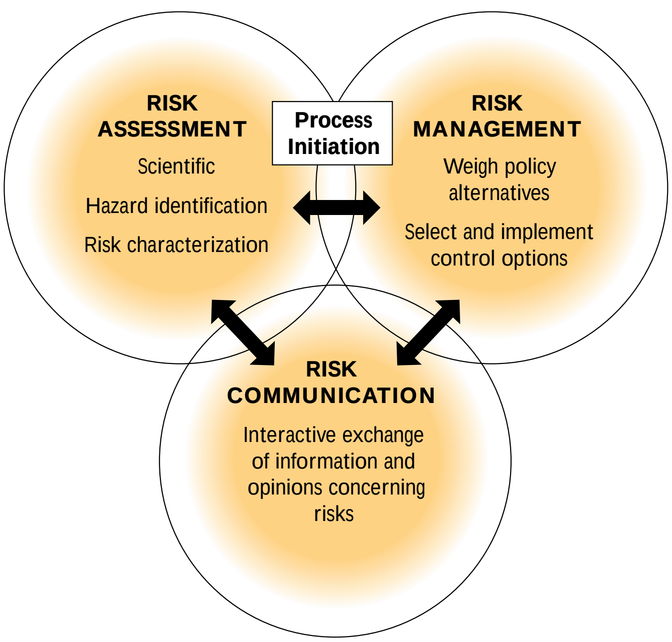

FIGURE 2
Schematic diagram of risk analysis, a process that involves the merging of scientific assessment, practical management, and ongoing communication.

McNab, Alves, Lammerding, Stahevitch, and Morely, 1996. Risk assessment models of Ontario Ministry of Agriculture, Food, and Rural Affairs. OMAFRA, Guelph, Canada.

Risk assessment methods have proven to be effective in evaluating the safety of chemicals, such as food additives and pesticides, and in determining tolerable levels of pesticides and other toxic substances. The movement to assess the risk of microbial infections and intoxications has only been instituted in the last few years. Risk assessment of foodborne disease is more complex than risk assessment of pesticide residues because microbes multiply and change their properties depending on the conditions they encounter. Microorganisms can enter the food supply at many different points and from many different sources. Risk assessments of foodborne disease must take into account the complexity of food production, processing, distribution, and preparation, the prevalence of pathogens in all sectors of the food chain, and the capacity for selected microbial pathogens to multiply in each sector.

The primary difficulties associated with the completion and validation of risk assessments associated with foodborne microbial pathogens are insufficient data on the parameters detailed above and a lack of sufficiently advanced models. Development of accurate data on the dynamics of the ecological systems involved, the role of microbial adaptation, and the antimicrobial efficacy of interventions would reduce the uncertainty associated with exposure assessment and hazard characterization after correlation. This, in turn, would improve the risk characterization and the value of the risk assessment in decision-making. Sophisticated analytical procedures are essential for modeling the wide set of interactions involving existing or contaminating microorganisms, and efforts to date are promising.

The USDA, with assistance from the FDA, has developed a risk assessment model for evaluating the contamination of shell eggs and egg products with *S. enteritidis*. This model has also been used to evaluate the importance of refrigeration for the prevention of subsequent foodborne disease (Whiting and Buchanan, 1997). A quantitative risk assessment model has been developed for *E. coli* O157:H7 in ground beef hamburger (Cassin, et al., 1998), and additional risk models are being developed. As promising as these models are, more fundamental and sophisticated models of product-specific food illness will be needed in the future. Fortunately, rapid advances now occurring in the computer industry are in the process of providing the computing power needed to support these new models.

Risk assessments can be used for many tasks, including research priority setting, predicting adverse health effects, and assessing the impact of new risk reduction strategies. All of these are important to the food industry. Moreover, development of experimental techniques and experimental design would be more rational and consistent if guided by a risk assessment context. Risk assessment logically leads to risk management, where policy alternatives can be discussed. Risk management techniques are used to develop science-based actions to mitigate hazards. However, it can be difficult to assess from a risk management standpoint who is responsible for what aspects of safety across the food chain. The respective roles and responsibilities of the various stakeholders—i.e., producers, processors, and consumers—need to be clarified. Although much of the food industry has become proficient at risk management within its domain, an emphasis on food safety and hazard prevention has not been adequately communicated to consumers. In many instances, effective risk management practices will require regulators to establish acceptable levels of risk through effective communication with consumers, industry, and others.

The applicability of mathematical modeling to risk assessment. Mathematical modeling is the next logical step in the evolution of our understanding of microbial ecology (both in environmental and clinical settings). Predictive microbiology seeks to model the relations between microbial growth and environmental factors by using mathematical equations. The uses of mathematical modeling technologies are not limited to practical applications in the area of food safety. The types of analysis now being developed for risk assessment applications have wide applicability for analyzing a variety of microbial ecosystems. For such methodologies to be useful to the scientific community, however, the application of programs using these methods should be accessible to scientists who are not experts in mathematical modeling.

Risk assessment techniques, especially those using mathematical modeling, hold great promise for increasing the sophistication of microbiological studies, especially in the area of food safety. These tools could have an impact similar to that of the molecular biology techniques now widely being used. Funding programs and agency collaboration will be needed to promote the adoption of these technologies. Methods development generally requires special funding programs to support the interdisciplinary work required to set up such models because it is not the type of hypothesis-driven research currently favored by grant review panels.

Estimated Costs of Foodborne Illnesses

As more and better data are collected and more sophisticated models are developed, greater quantification is possible in risk assessments of particular food safety problems. One of the variables in these assessments is the estimated cost of foodborne illness. The Economic Research Service (ERS) of the USDA publishes cost-of-foodborne-illness estimates for seven foodborne pathogens. Estimated medical costs and productivity losses are calculated over the lifetime of the infected individuals. Both acute cases and chronic complications are included in the medical outcomes, often on the basis of data provided by the CDC. Based on the extent of the medical treatment, cases are classified into five severity groups: those not visiting a physician, those who visit a physician, those who are hospitalized, those who die prematurely, and those who develop chronic complications. For each severity group, medical costs are estimated for physician and hospital services, supplies, medications, and special procedures unique to treating the particular foodborne illness. Such costs reflect the number of days of treatment, average cost per treatment or service, and the number of patients receiving this treatment or service (Buzby and Roberts, 1997; Buzby, et al., 1996).

Productivity losses for persons for a few days or weeks are approximated by the Bureau of Labor Statistics and include changes in average weekly earnings plus fringe benefits. For those unable to resume their normal job (either because of disability requiring a switch to a less demanding job or death), two methods—one high and one low—of estimating losses are used. The low estimate is based on a formula for lost lifetime earnings and household production (Landefeld and Seskin, 1982). The high estimate is based on the "risk premiums" in labor markets, where numerous studies have found a $5 million value per statistical life (Viscusi, 1993).

The most recent ERS estimates for the costs of acute infections (and the potential chronic complications) for seven foodborne pathogens range from $6.6 billion to $37.1 billion per year (Table 4; Buzby and Roberts, 1997). The FDA, in its evaluation of food safety programs, uses only the high estimate for productivity losses but adjusts the latter for the age of the person. Economists working at the ERS, FDA, CDC, and in academic institutions are developing and refining mathematical methodologies to improve these estimates.

Estimates of the productivity costs of foodborne illness are likely to be greater in the future because the means of arriving at these estimates are improving. The current estimates only consider societal resources used in direct response to human foodborne illness. Improvements in estimating the overall costs will need to include estimates of the price consumers are willing to pay for improved food safety. As our knowledge of the effects of foodborne illness over one's life span increases, it is also likely that more pathogens will be

TABLE 4:
Economic costs attributed to seven foodborne illnesses in 1996[1]

	Estimated foodborne illness		Estimated foodborne illness costs	
	Cases	Deaths	Human capital approach[2]	Labor market approach[3]
Pathogen, acute illness, and complication	Number		Billion 1996 $	
BACTERIA:				
Campylobacter jejuni or *coli*				
Campylobacteriosis	1,100,000-7,000,000	110-511	0.7-4.4	1.2-6.7
Guillain-Barré Syndrome	293-2,681	6-53	0.1-1.3	0.4-3.4
Subtotal	N/A	116-564	0.8-5.7	1.6-10.1
Clostridium perfringens				
C. perfringens	10,000	100	0.1	0.5
Escherichia coli O157:H7				
E. coli O157:H7 disease	16,000-32,000	40-80	0.05-0.1	0.1-0.2
Hemolytic uremic syndrome[4]	800-1,600	23-46	0.1-0.2	0.2-0.4
Subtotal	N/A	63-126	0.16-0.3	0.3-0.7
Listeria monocytogenes[5]				
Listeriosis	928-1,767	230-485	0.12-0.26	1.2-2.3
Complications	22-41	0	0.03-0.05	0.1-0.2
Subtotal	N/A	230-485	0.1-0.3	1.3-2.4
Salmonella (non-typhoid)				
Salmonellosis	696,000-3,840,000	870-1,920	0.9-3.6	4.8-12.3
Staphylococcus aureus				
S. aureus intoxications	1,513,000	454	1.2	3.3
PARASITE:				
Toxoplasma gondii[6]				
Toxoplasmosis	260	40	0.4	0.1
Complications	1,560	0	3.28	7.7
Subtotal	N/A	40	3.3	7.8
Total	**3,300,000-12,400,000**	**1,900-3,700**	**6.6-14.5**	**19.6-37.1**

Notes:

1 Cost estimates are in 1996 dollars. N/A = Not applicable. Subtotal and totals may not add due to rounding. Totals are rounded down to reflect uncertainty of the estimates.

2 The Landefeld and Seskin approach is basically a human capital approach, increased by a willingness to pay multiplier, and estimates the cost of a premature death, depending on age, to range from roughly $15,000 to $2,037,000 in 1996 dollars.

3 This labor market approach values the cost of a premature death at $5 million.

4 Hemolytic uremic syndrome (HUS) is characterized by kidney failure. HUS following foodborne *E. coli* O157:H7 infections causes 44-90 acute illness deaths and 33-62 chronic illness deaths.

5 Includes only hospitalized patients because of data limitation.

6 Includes only toxoplasmosis cases related to fetuses and newborn children who may become blind or mentally retarded. Some cases do not have noticeable acute illness at birth but develop complications by age 17. Does not include all other cases of toxoplasmosis. Another high-risk group for this parasite is the immunocompromised, such as patients with AIDS or cancer.

Adapted from Buzby and Roberts, 1997.

identified. This will enable more accurate cost estimation in the future, especially given the potential involvement of other chronic sequelae that we cannot now identify.

Comparative Risk Evaluation

Risk assessors currently rely on historic data obtained from controlled clinical studies with enteric pathogens, and this information needs to be updated. These studies have often been performed with multiple strains of a pathogenic microorganism, complicating the analysis. Although comparisons in the level of illness have been made between human and animal dosing studies, data from animal models may not be applicable to estimating infectious dose in humans. From these very limited data sets, extrapolations to low dose are made in an effort to identify minimal infective human doses. These data do not include studies of the effects on illness when the organism is present in different food vehicles.

Dose response is an outcome of interdependent effects among organism, host, and food vehicle. It thus appears improbable that a single response to a hazard in a given food product could be developed. In short, there is no magic bullet for each hazard. Nonetheless, we have been forced until now to develop a "one size fits all" model to accommodate the data. The FDA has awarded grants to carry out comparative foodborne illness dosing studies using human volunteers and appropriate animal model systems with the same strains of selected enteric pathogens grown under identical conditions. This should provide limited but improved data sets for modeling purposes.

Comparative risk evaluations of similar situations, e.g., which pathogen or situation presents a higher risk, can be useful for setting research and regulatory priorities. But broad risk comparisons are neither well received nor well understood by the public (Sandman, 1987). It is not appropriate to compare the risk of foodborne illness to the risk of being struck by lightning or the risks associated with smoking. The public, however, does appreciate knowing the actual risks or probabilities of developing illness associated with eating specific foods. This should be used to develop meaningful comparisons to better educate the public about food safety risks.

Areas of Future Research

Cooperation among clinical microbiologists, epidemiologists, food microbiologists, and veterinary microbiologists is needed to improve our understanding of pathogen sources, foodborne disease incidence, effective control measures, mechanisms of resistance, and dose-response relations, particularly for those foodborne pathogens that impact specific high-risk populations. The possible involvement of foodborne disease in chronic disease syndromes, such as reactive arthritis, hemolytic uremic syndrome, rheumatoid arthritis, Guillain-Barré syndrome, Crohn's disease, and ulcers, also needs to be investigated. Continued study of sporadic cases of foodborne illness may help identify additional factors or vehicles implicated in or responsible for the transmission of foodborne pathogens. This study could be accomplished through the expansion of FoodNet to provide for the intensive investigation of such factors as part of its charge. It is generally assumed that sporadic cases of campylobacteriosis, salmonellosis, and illnesses caused by enterohemorrhagic *E. coli* are foodborne, but this has not been documented.

Many epidemiological studies begin with illness and work backwards but stop at the first point at which a problem or deficit becomes apparent. This system of tracing illnesses back from the infected individual to the offending food source is termed "trace back," but it may not provide the entire picture of the problem. In many cases, the ability to conduct trace backs is made difficult because of the length of time that elapses after the infected person becomes ill and the likelihood that the infected food is no longer available for testing. Instead of relying solely on making trace backs more extensive, a more proactive measure would be to evaluate each stage of the food supply system to determine the adequacy of procedures at each point.

Large outbreaks of foodborne illness that meet selective characteristics are a rich source of information that can be helpful for risk assessment. Such outbreaks present opportunities to conduct more intensive, case-controlled investigations. These studies should include quantitative microbiological investigations of the suspected food sources to define infective dose, as well as stool cultures to determine infection (shedding) and blood collection to determine immune response. Cases of ill and well persons that ate the same contaminated food should be included in the study to identify host factors that predispose individuals to symptomatic infection. These outbreaks can also be studied prospectively to identify possible sequelae or effects on fetuses. In addition, follow-up studies can be made to determine the effectiveness of recall procedures and risk communications. Such large outbreaks should also be viewed as opportunities in which the public can be apprised of the causes, consequences, and responses to foodborne illness.

The effectiveness of different communication strategies to targeted audiences should be evaluated. Risk communication is complicated when different messages regarding safe food concerns are transmitted to the public. The wide variability of the risk assessment approaches used by different regulatory agencies, e.g., USDA and FDA, and the disparate messages resulting from these differences, often confuse the public.

THE FOOD SAFETY COMMUNITY

Scientists have played an important role in identifying challenges to food safety and in investigating their possible solutions. While more research is needed, coordinated efforts among industry, government, the news media, consumers, and professional societies are also required for continued improvement in the safety of the food supply. The overall "ecology" of the food supply has political, economic, and social dimensions that affect food safety. The role of the scientific community encompasses research to enhance knowledge of the sources, ecology, survival, proliferation, control, resistance mechanisms, and methods of detection of pathogens. The respective roles of the other stakeholders in the food supply are reviewed in turn below.

Role of the Food Industry

Industry has the primary responsibility for ensuring the safety of the foods produced and therefore should employ the most current and effective production controls. Examples of newer control interventions in the meat processing industry include the use of steam pasteurization, hot water or chemical decontamination, and steam vacuuming (Jay, 1997; Sofos and Smith, 1998). An industry-implemented systems approach to ensuring food safety, such as HACCP, is preferable to government-mandated, hands-on inspection. The HACCP approach is based on scientific and systematic data collection and is practiced by an increasingly large segment of the food industry. Although a HACCP program is not required in all segments of the food industry, the adoption of such an approach should be strongly encouraged. However, small food processors might need assistance to develop and implement food safety assurance programs.

The food industry should also be involved in research relating to the safety of their products and in risk assessment and management of these products. There must be continued communication among industry personnel, researchers, and regulators to promote food safety awareness. Companies conduct considerable research on the safety of their respective foods, but this knowledge is considered proprietary information and is not routinely shared with other companies, the government, or the public. The microbiological specifications and guidelines for ingredients and foods must be made available to these other interested parties. Establishment of a central clearinghouse maintained by an independent group to ensure the confidentiality of truly proprietary information would be one mechanism for doing so.

Employers should instruct food service employees on safe food-handling practices. The quality and extent of this instruction varies, and local regulations pertaining to food safety practices thwart uniform education efforts. The FDA recommended optimal food-handling standards in the Food Code issued in 1993 and revised in 1999; however, the Code has not been adopted in its entirety by most states and local authorities. Therefore, the FDA Model Food Code should be adopted uniformly by local jurisdictions. Short, effective, professionally prepared instructional videos would facilitate the implementation of this code throughout the country. Employers or supervisors should continually monitor employee compliance with good food-handling practices.

Role of the Government

The government's role in ensuring food safety is manifold. It extends from the development of an appropriate regulatory system for the oversight of industry to funding research and informing the public about food safety issues. Ideally, the federal government needs to be responsive to and work in partnership with the food industry, consumer groups, the media, state and local governments, and other organizations with an involvement in food safety. Government policy should be based on scientific principles but there is often a lack of sound data on which to formulate policies. Research and development spending for food safety is now minimal and should be increased.

There is a myriad of departments, agencies, and programs within the federal government that have jurisdiction over food safety-related issues. The Department of Health and Human Services (HHS) oversees two agencies with food safety responsibility: the CDC and the FDA. Food safety-related programs at the FDA include the Center for Food Safety and Applied Nutrition (CFSAN), the Center for Veterinary Medicine (CVM), and the Joint Institute for Food Safety and Applied Nutrition , a collaborative effort among CFSAN, CVM and the University of Maryland.

The USDA houses the Agricultural Marketing Service (AMS), the Animal and Plant Health Inspection Service (APHIS), the Agricultural Research Service (ARS), the Cooperative State Research, Education and Extension Service (CSREES), ERS, the Federal Grain Inspection Service, and the Food Safety and Inspection Service (FSIS). The FSIS does not conduct its own research but depends on others, particularly the ARS, to provide reliable scientific information. APHIS currently has a mandate for on-farm work but is prohibited from dealing with food safety issues.

Other entities in the federal government with food safety responsibilities include the National Institutes of Health, the National Marine Fisheries Service, the Environmental Protection Agency, and the Department of Defense. At the present time, there is no evidence that federally sponsored research is coordinated or prioritized. The National Academy of Sciences undertook a study in 1998 to assess the effectiveness of the current food safety system in the United States. The National Academy concluded that the current system is effective but noted that statutory revisions were necessary to ameliorate the system's fragmented structure and ensure that policy was more science based. Federal agencies should demonstrate that they set research priorities, that the research performed matches those priorities, that there is coordination of research across programs, and that research programs and projects (new and continuing) are peer reviewed and demonstrate value. This would cover all research funded by federal agencies. Agency Science Advisory Boards should be in place to review priorities and programs.

Other recent government activities designed to maintain and improve food safety include establishment of the Joint Institute for Food Safety Research. This White House initiative was formed to review ongoing research programs, set goals and priorities, foster collaboration among other programs, and develop budget initiatives. In the fall of 1998, President Clinton established the Council on Food Safety (CFS), cochaired by the Agriculture Secretary, the HHS Secretary, and the Director of the Office of Science and Technology Policy. The Council has been asked to develop a comprehensive federal food safety plan and to consult with the JIFSR to develop plans for food safety research. The National Alliance for Food Safety, a public-private partnership composed of 20 universities, government agencies (ARS and CSREES), and industry and consumer groups was also recently established. The mission of the Alliance is to enhance public confidence in the safety of the food system.

Before l993 and the widely publicized multistate *E. coli* OI57:H7 outbreak, the news media had not played a major role in communicating microbiological food safety issues to the public.

International policy issues. The objective of one facet of international trade agreements is to increase food trade between countries. Increased international trade may lead to food safety problems because of differences in food production practices and inspection procedures. Members of the World Trade Organization, established under the General Agreement on Trade and Tariffs, are obliged to ensure the compatibility of regulations governing food safety and quality, including verification and audit systems such as HACCP. However, some countries may claim that the requirement for HACCP presents a Technical Barrier to Trade violation under GATT (Garrett et al., 1997).

The United States can play a critical role in helping developing countries acquire the infrastructure needed for improving food production, food safety, and public health. Such action is mutually beneficial. Risk assessment and harmonization of standards should be done internationally, though not at the cost of weakening domestic standards. The large-scale production of food together with its rapid delivery across international borders make it imperative that systems are devised for reporting outbreaks of foodborne disease. The strengthening of ties with groups such as the International Commission on the Microbiological Specifications of Foods is crucial for maintaining food safety. The World Health Organization can also have an impact on food safety by improving disease surveillance and establishing public health standards and definitions.

International bodies such as the Codex Alimentarius Commission (Codex) may be increasingly relied on to establish acceptable guidelines and limits for microbial numbers and pathogens as well as to set acceptable levels of risk. The Codex International Food Standards Programme is improving quantitative and qualitative risk assessment techniques. With shrinking resources available at the national level and an increasing variety of foodstuffs being traded, there needs to be a concomitant increase in food safety compliance and verification at the international level. It is essential that the United States continue to participate in global efforts to curb foodborne illness.

Role of the News Media

Before l993 and the widely publicized multistate *E. coli* OI57:H7 outbreak, the news media had not played a major role in communicating microbiological food safety issues to the public. The previous media emphasis had long been focused principally on food additives or pesticides. Subsequently, local and national level media have played a major role in disseminating food safety issues to the public, although unfortunately there has been some uninformed or biased scientific opinion presented to the public in such matters. Examples of the negative aspects of media coverage include raising public expectations of safe food to an unrealistic level, occasional inaccurate or unbalanced statements, and the promotion of unfounded fears as to the overall safety of the food supply. However, the media have increased public awareness of food safety, mostly by educating consumers about practices that may be implemented in the home and by increasing public support for food safety initiatives.

The public receives most of its information about food safety from the news media and from advocacy groups. Usually, these communications are in response to foodborne illness crises or outbreaks. Additional educational sources have been "safe food labels" and instructional materials prepared by the government or industry as well as a plethora of information posted on the Internet.

The news media tend to treat consumers as victims of foodborne illness without always pointing out the consumer's responsibility to observe safe food-handling practices. The media requirement for simple, to-the-point information also often leads to their translating the cautious language of scientific reports into simplistic overstatement. Scientists should take the opportunity to devise ways in which to educate the media about the complexity of the issues involved with foodborne illness. In general, if a company is faced with a specific food safety-related problem, it fares better if it quickly and honestly acknowledges the problem in comments to the press, demonstrates concern for the consumer, and works to solve the problem in a timely manner. Government and industry need to engage the news media at both the local and national levels to improve the balance and accuracy of the media's coverage of food safety issues.

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Role of the Consumer

It has long been known that most cases of documented foodborne illness are attributed to mishandling, or other problems, in the home or food service establishments, including restaurants, cafeterias, delicatessens, schools, nursing homes, hospitals, prisons, street vendors, and day care centers. In addition, most foodborne infections are not contracted in large, concentrated outbreaks, although these episodes receive the most publicity. The consumer has an important role to play in assuring that pathogen-killing steps are taken before food is consumed and that cross-contamination does not occur. The consumer must make informed decisions about food choices and handle and maintain food in a safe and responsible manner. To assist the consumer, there must be improved consumer education about food safety. Research should be conducted to determine what factors influence consumer food safety behaviors. These efforts will help the consumer buy and prepare products with safety in mind (Knabel, 1995; Yang, et al., 1998). In addition to being educated about hazardous organisms, the public needs to learn about the positive and protective role of beneficial organisms.

Role of Professional Societies

Professional societies, such as the American Society for Microbiology (ASM), could play a valuable role in bringing scientists from different areas together to provide a multidisciplinary approach to food safety issues. Collaboration among scientists from the areas of clinical microbiology, food microbiology, animal health and production, microbial ecology, and epidemiology might be an effective means of solving some of the problems noted in this report. The ASM should encourage the training of individuals with the ability to undertake this type of multidisciplinary research. The present state of postgraduate education and the current means of training older professionals are not appropriate to this purpose. ASM needs to encourage changes in the educational structure and emphasis of universities and other training institutions that would better prepare students for involvement in this field. The editorial policy of ASM journals should also facilitate these goals by recognizing and supporting the importance of multidisciplinary research.

Professional certification programs. The American Academy of Microbiology, through sponsorship of the American College of Microbiology, offers a certification program for Food and Dairy Microbiology, but it has not been perceived that there is industry demand for this program or that this type of certification conveys any additional expertise. It is important that well-trained food microbiologists and food safety specialists be available to the food industry. Industry should be encouraged to collaborate with academia to ensure that adequate curricula are in place. In the past 15 years, some of the "classical" food microbiology education has been largely replaced by an emphasis on biotechnology or molecular and cell biology. Consequently, there is now a shortage of qualified food microbiologists. This issue should be addressed through coordinated strategies and efforts by academia, government agencies, scientific societies, trade associations, and the industry. Food microbiologists receive excellent education and training in formal food science programs at the university level.

There are efforts to provide accreditation for several groups and activities. The National Sanitation Foundation International certifies materials and equipment design to national and public health standards, and the Food Laboratory Accreditation Working Group, part of the Association of Official Analytical Chemists International, provides standards for laboratory operations and laboratory methods. Good laboratory practices should be emphasized and maintained in industrial, government, and private contract laboratories. Laboratory accreditation should be followed by periodic verification. The involvement of general clinical laboratories in food analysis should be allowed only after appropriate personnel training and accreditation. Laboratory operating procedures and their verification should be harmonized and equivalent worldwide. The food industry should be aware of these procedures and requirements and be strongly encouraged to use only accredited laboratories. This particularly applies to small companies that often do not have specific knowledge or expertise in food microbiology.

Communication. The American Society for Microbiology, in concert with other professional societies, e.g., the Institute of Food Technologists and the International Association for Food Protection (formerly, International Association of Milk, Food and Environmental Sanitarians), can play a major role in the communication of food safety issues through several avenues. Scientists and educators, under the auspices of scientific societies, regulatory agencies, consumer advocacy groups, and the industry, should develop educational activities and programs. These efforts can then be applied at different levels and for various groups including students in elementary and secondary schools, food processing line workers and food service food handlers, consumers, news media personnel, analytical laboratory personnel, clinicians, legislators, regulators, and the public. Educational and training material should include printed or video materials, which may also be available through the Internet.

Understanding of food safety issues can be enhanced in dissemination of information to the public. The leadership of the Food Microbiology Division and the Chair of the Agricultural, Food and Industrial Microbiology Committee of the Public and Scientific Affairs Board in ASM could provide well-trained spokespersons to the press and others seeking authoritative voices on the issues. A roster of scientific speakers with expertise in the food safety area could be developed and made available to speak at professional meetings.

The ASM could also develop links to the International Food Information Council (IFIC). The IFIC prepares a Food Insight Media Guide as a source book for information on food nutrition and safety. The IFIC provides background information on various issues and lists experts who are willing to talk with the media. The ASM can also serve as a source of expert information in response to proposed regulations published in the Federal Register.

Short courses containing a food safety emphasis can be jointly developed with other professional societies and delivered in conjunction with annual meetings. Professional societies can recognize the achievements of members of the food industry or academia who have most improved food safety by inventing or adopting new technologies, showing the most improvement in their safety records, or sharing data with the public. Societies can also create databases to use for risk assessments or for designing HACCP programs, and they can publish food safety information on the Internet relating to firms (legal liability information, data on pathogen levels, FSIS compliance records, etc.).

RECOMMENDATIONS

Many of the recommendations developed by colloquium participants focused on ways of improving consumer understanding of safe food practices. These include, but are not limited to, the following:

- development of more appealing safe food-handling instructions to be displayed at the point-of-sale, e.g., in the supermarket;
- creation of public service announcements for radio and television containing food safety information from the appropriate government agencies;
- dissemination of brochures about food safety to individual households, similar to the program developed by the Surgeon General for AIDS awareness;
- development of safe food-handling modules aimed at school-aged children, e.g., the "FightBac" program initiated by the USDA, which can be taught in the school or by television on science-based programs;
- incorporation of safe food-handling practices on television cooking shows to demonstrate appropriate procedures to viewers;
- dissemination of information by Extension Specialists in rural communities; and
- determination of the most effective educational materials and methods for inducing behavioral changes in consumers' food-handling practices.

In addition to the importance of promoting safe food-handling practices, colloquium participants emphasized the contributions of enhanced surveillance, continued research on microbial ecology, and the use of risk assessment techniques to the process of improving the safety of the food supply. A more thorough tracking of sporadic cases of foodborne disease will provide a better understanding of where improvements in food safety need to be made. More needs to be learned about the ecology of pathogens and the normal microbiota of foods in order to develop strategies to reduce pathogen incidence by competitive exclusion. Finally, continued development and systematic application of risk assessment techniques will provide a framework for integrating the various challenges to food safety along the farm-to-table continuum and promote the use of specific targeted interventions.

It was also recommended that the utility of the concept of "zero tolerance" be reevaluated. Zero tolerance limits may not be achievable with the increasing ability to detect smaller numbers of organisms, and the numbers of organisms detected at these lower levels may have little relationship to pathogenicity. Compliance to zero tolerance level requirements may have little correlation with a decreased incidence of foodborne illness for a particular organism. The nonrandom incidence of some pathogens in foods and the associated limitations of sampling protocols would still be a concern.

Finally, participants noted that a lack of data about specific pathogen levels and their significance have resulted in weak economic incentives for finding solutions to current food safety problems. In addition to developing science-based government regulatory policies, ways of creating economic incentives to encourage firms to adopt innovations in food safety need to be explored. A research initiative with government, industry, academic, and consumer participation could be established to develop and evaluate options for improving food safety.

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