

A report from the American Academy of Microbiology



Preharvest Food Safety and Security



AMERICAN
SOCIETY FOR
MICROBIOLOGY

By Richard E. Isaacson, Mary Torrence and Merry R. Buckley

Copyright © 2004
American Academy of Microbiology
1752 N Street, NW
Washington, DC 20052
<http://www.asm.org>

This report is based on a colloquium sponsored by the American Academy of Microbiology held December 5-7, 2003, in Perthshire, Scotland.

The American Academy of Microbiology is the honorific leadership group of the American Society for Microbiology. The mission of the American Academy of Microbiology is to recognize scientific excellence and foster knowledge and understanding in the microbiological sciences.

The American Academy of Microbiology is grateful for the generous support of the following:

American Association of Avian Pathologists
Agricultural Research Service, U.S. Department
of Agriculture
Association for Veterinary Epidemiology
and Preventive Medicine
Bayer AG, Health Care
Cooperative State Research Education and Extension
Service, U.S. Department of Agriculture
National Pork Board
Pfizer Animal Health
Scotland Center for Infection and Environmental Health
University of Glasgow, Scotland
U.S. Food and Drug Administration

The opinions expressed in this report are those solely of the colloquium participants and may not necessarily reflect the official positions of our sponsors or the American Society for Microbiology.

**Board of Governors,
American Academy of Microbiology**

Eugene W. Nester, Ph.D. (Chair)
University of Washington

Kenneth I. Berns, M.D., Ph.D.
University of Florida Genetics Institute

Arnold L. Demain, Ph.D.
Drew University

E. Peter Greenberg, Ph.D.
University of Iowa

J. Michael Miller, Ph.D.
Centers for Disease Control and Prevention

Stephen A. Morse, Ph.D.
Centers for Disease Control and Prevention

Harriet L. Robinson, Ph.D.
Emory University

Abraham L. Sonenshein, Ph.D.
Tufts University Medical School

George F. Sprague, Jr., Ph.D.
Institute for Molecular Biology, University of Oregon

David A. Stahl, Ph.D.
University of Washington

Judy D. Wall, Ph.D.
University of Missouri

Colloquium Steering Committee

Richard E. Isaacson, Ph.D. (Co-Chair)
*Department of Veterinary Pathobiology,
University of Minnesota*

Mary Torrence, D.V.M., Ph.D. (Co-Chair)
U.S. Department of Agriculture

Thomas E. Besser, D.V.M., Ph.D.
*Department of Veterinary Microbiology and Pathology,
Washington State University*

Ian A. Gardner, Ph.D.
*Department of Medicine and Epidemiology,
University of California, Davis*

Lee-Ann Jaykus, Ph.D.
Food Science Department, North Carolina State University

James D. McKean, D.V.M.
Animal Sciences, Iowa State University

Stuart Reid, Ph.D.
*Veterinary Informatics and Epidemiology,
University of Glasgow, Scotland*

Carol A. Colgan
Director, American Academy of Microbiology

Colloquium Participants

J. Daniel Collins, Ph.D.

Department of Large Animal Clinical Studies, Faculty of Veterinary Medicine, University College, Dublin, Ireland

Patricia A. Conrad, Ph.D.

Department of Veterinary Medicine, University of California, Davis

Gordon Dougan, D.Phil.

Centre for Molecular Biology and Infection, Imperial College of Science, Technology, and Medicine, London, England

David L. Gally, Ph.D.

Zap Laboratories, Medical Microbiology, University of Edinburgh, Scotland

Linda J. Harris, Ph.D.

Department of Food Science and Technology, University of California, Davis

Charles Hofacre, Ph.D.

Department of Avian Medicine, University of Georgia

Roger P. Johnson, Ph.D.

Laboratory for Foodborne Zoonoses, Health Canada, Guelph, Ontario, Canada

Charles B. Kasper, Ph.D.

University of Wisconsin, Madison

Anna Lammerding, Ph.D.

Animal and Plant Health Directorate, Agriculture and Agri-Food Canada, Guelph, Ontario, Canada

Jay F. Levine, D.V.M., M.P.H.

Department of Farm Animal Health and Resource, North Carolina State University

Dominic Mellor, Ph.D.

Department of Veterinary Clinical Studies, University of Glasgow, Scotland

Anne Morner, D.V.M.

Bayer Health Care, Animal Health Division, Monheim, Germany

Michael T. Morrissey, Ph.D.

Astoria Seafood Laboratory, Oregon State University

William Reilly, D.V.S.M.

Gastrointestinal and Zoonoses Section, Scottish Centre for Infection and Environmental Health, Glasgow, Scotland

Linda Saif, Ph.D.

Food Animal Research Program, Ohio State University

Randall S. Singer, Ph.D.

Department of Veterinary Pathobiology, University of Illinois

Linda R. Tollefson, D.V.M.

Center for Veterinary Medicine, U.S. Food and Drug Administration

Elizabeth Wagstrom, D.V.M.

National Pork Board

Irene Wesley, D.P.H.

U.S. Department of Agriculture

Thomas E. Wittum, Ph.D.

Ohio State University, College of Veterinary Medicine

Qijing Zhang, Ph.D.

Department of Veterinary Microbiology and Prevention, Iowa State University

EXECUTIVE SUMMARY

A colloquium was convened in Perthshire, Scotland, December 5-8, 2003, by the American Academy of Microbiology to deliberate preharvest food safety and food security strategies. Professionals with expertise in veterinary medicine, agriculture, plant science, food safety, and microbiology discussed current practices in preharvest food safety, problems posed by pathogens on the farm, research needs in the field, and communication and education priorities.

Recent major outbreaks of foodborne illness continue to heighten our awareness about the complexity of the farm-to-fork continuum and the relevance of the on-farm or preharvest role. For example, outbreaks of *Cyclospora* in Guatemalan raspberries, hepatitis A from Mexican green onions, and norovirus from British Columbian oysters all began with contamination at the preharvest level. For many food products, it can be difficult to prevent transmission of pathogens to consumers once the food leaves the farm, since post-harvest decontamination steps, if available, are not always effective. For food products eaten raw, like fruits, vegetables, nuts, and some seafood, there is no cooking process to inactivate pathogens. Another complication can be home preparation where raw food products, like meat, can be the source of pathogens to other items in the food preparation environment before cooking. There are many steps in the process that brings food from the farm to the table; each step provides opportunities for contamination and, ultimately, risk of foodborne illness. This colloquium only considered preharvest food safety, although we recognized that it is not the only or, in some case, the most critical, stage of food production. However, cost effective interventions with the potential of reducing levels of contamination can be useful in the continuum of food production.

Outside of basic hygiene practices, few food safety controls are in place in food production environments (preharvest) because not enough information is available on what would control foodborne pathogens. There are multiple needs for data: systematic surveillance would provide baseline data on the prevalence of pathogens, and epidemiologic research could help identify effective controls. Comprehensive and transparent risk assessments on preharvest issues are needed

to continue to identify risk mitigation priorities and to provide comparisons among intervention strategies.

The human pathogens of concern in preharvest environments include a wide array of viruses, parasites, and bacteria that can have a range of effects and severity, depending on pathogen-specific and host-specific properties. Due to differences in cultivation practices and wealth of resources, the organisms of concern on farms in industrialized nations and in developing countries are likely to be quite different.

Admittedly, eliminating pathogens from the preharvest environment would be nearly impossible. A more practical goal for preharvest food safety interventions is to reduce pathogen numbers to levels that will reduce the degree of hazard to public health. Unfortunately, since there is not always a definitive link between preharvest food safety and public health, and there are many factors in between, it will first be important to understand the role of preharvest contamination and control strategies on the overall burden of microbes in our food supply. This is complicated because some foods are marketed direct from the farm to retail (produce), while other products have intermediate processing steps (meats), and their impacts on importance of on-farm measures may be different. Furthermore, this may afford only temporary success, since the pathogens may reproduce and disseminate during other steps in the farm-to-fork continuum. Indeed, many factors play roles in determining the numbers of pathogens in food production environments, including diet, seasonal factors, and microbial symbioses, among others.

In light of global concerns about bioterrorism, biological security on the farm is an even bigger concern. A number of security-sensitive points in food production processes were discussed, and priorities for security measures were identified.

Although progress has been made, our understanding of the epidemiology of foodborne pathogens on the farm and the best ways to manage their risks is limited at best. A number of specific preharvest food safety research needs were identified, including validation and development of interventions, development of better tools for pathogen detection and enumeration, and investigation of the effects of interventions on microbial community dynamics.

INTRODUCTION

Food safety encompasses complex interactions among animals, humans, and the environment. Some foodborne organisms are pathogenic to animals, while others are commensals in animals. Food safety, in this report, encompasses foodborne pathogens and their effect on public health. This would include colonization, persistence, and shedding of the pathogens from animals, leading to contamination of food products. An overarching theme is that food safety is important only to the extent that it affects public health.

Human pathogens can be found in food of all kinds, from meat and poultry, to fish and shellfish, to fruits and vegetables. Oftentimes, these foodborne pathogens are acquired on the farm, before the food even reaches processing facilities, distribution networks, businesses, and homes. In recent years, a number of major outbreaks of foodborne illness have been linked to contamination on the farm, including a recent outbreak of Hepatitis A in Pennsylvania resulting from the consumption of contaminated green onions originating from a farm in Mexico. In this outbreak, over 650 people were sickened by eating the onions, which had been contaminated by farm workers in the field. Three people died.

Unfortunately, pathogens acquired during preharvest cannot always be inactivated by meticulous food handling or cooking, since many foods are eaten raw, as in the case of the green onions. Other foods, such as meat and poultry, can be the source for the spread of contamination to other foods in the kitchen before being cooked. Nor can all pathogens be removed reliably during processing. In some instances, pathogen numbers may actually increase after processing (post-harvest) and during transportation, storage, and retail.

Irradiation has been suggested by some as a solution to controlling contamination. While irradiation is effective against many pathogens, it is not effective against all pathogens (e.g. enteric viruses) and may not be suitable for all products. It adds some cost to products, and the equipment used to irradiate the foods is not widely available. Irradiation can cause some significant sensory changes to the products, but it does increase shelf life. Irradiation has been successfully used to prolong shelf life of strawberries and has been used on imported spices. Nevertheless, this technique has not been widely accepted and to some consumers is an unacceptable practice.

Eating foods carries an inherent risk of foodborne disease. Fresh food is not sterile, and there is always a chance that foodborne pathogens may be a part of

your next meal. Preharvest food safety needs to encompass a range of strategies for limiting the establishment or proliferation of pathogens in food prior to harvest for human consumption. The goal of preharvest food safety and other food protection endeavors should not be to eradicate foodborne pathogens, which would be nearly impossible, but rather to reduce the risk of foodborne illness by minimizing the number of pathogens in food and the frequency, extent, and distribution of such contaminants in the preharvest phase. Food producers, scientists, and health officials can only aim to manage the problem of foodborne pathogens and limit the risks they pose. Risk assessment can be as valuable tool in evaluating the trade-offs between implementing interventions to prevent the transmission of foodborne pathogens and the payoffs in improving human health.

A colloquium was convened in Perthshire, Scotland December 5-8, 2003 by the American Academy of Microbiology to examine preharvest food safety and food security strategies. Professionals with expertise in veterinary medicine, agriculture, plant science, food safety, and microbiology discussed current practices in preharvest food safety, problems posed by pathogens on the farm, research needs in the field, and communication and education priorities.

For the purpose of the colloquium and this report, the term "preharvest" refers to the period of time when a food product is growing, prior to the harvest of the crop or livestock slaughter. Most food is grown on farms, as is the case with crops and meats, but other production environments exist. Shellfish, for example, are grown in seeded marine beds. To be concise, the term "farm" will be used in this report to refer to the diversity of confined production systems used to grow food and the environments surrounding livestock as they are transported to slaughter, including trucks or other vehicles and lairage.

CURRENT PRACTICES AND CONTROLS

Food safety funding and initiatives over the last five years have provided a better understanding of food safety and the prevalence of pathogens in pre- and post-harvest. Yet much more research, education, and extension work are needed. Systematic surveillance, improved detection methods, comprehensive risk assessment, and trade issues are examples of what must be considered for preharvest food safety in the future.

Some guidance documents, with particular attention to good manufacturing production practices have been developed commodity group organizations in an effort to enhance food safety. The implementation of these guidelines has been voluntary, and they are not standardized and vary among production environment, food animal species, and farm type. The seafood and fresh produce industries have provided leadership in the establishment, adoption, and application of widely accepted guidance documents (United States Food and Drug Administration (FDA), United States Department of Agriculture (USDA), Centers for Disease Control and Prevention (CDC)). The effectiveness of these controls has not been systematically evaluated and is open to debate, but the application of guidance documents and “good agricultural practices” in these industries are steps in the right direction for preharvest food safety. Guidelines and management practices for other commodities are in earlier stages. More comprehensive and science-based guidelines are needed.

There is a *Trichinella* control program for swine that is aimed at better animal health and food safety. This program, while narrow in focus because it is only for swine production, is an important demonstration of how risk factor based research can result in effective interventions. Vaccination has been proposed as another way to reduce foodborne pathogens, but the efficacy of these programs in reducing the number of illnesses in consumers has yet to be assessed. Vaccines have been useful to combat *Salmonella enteritidis* in chicken eggs, reducing the number of contaminated eggs. However, whether similar approaches can be used in beef or pork production remains unknown. Other approaches, such as competitive exclusion, in which livestock are inoculated with non-pathogenic bacteria to compete with pathogens, have also been tried with some success. Rigorous trials should be undertaken to validate the benefits of vaccination and competitive exclusion programs, both in controlling pathogens preharvest and the impact of these strategies on subsequent public health.

New interventions, designed around critical control points, are needed at the farm level to help break the cycle of disease. Critical control points are those steps in the preharvest environment at which controls can be applied to prevent the establishment or proliferation of the organisms responsible for foodborne illness. It has been proposed to use “Hazard Analysis and Critical Control Points” on the farm. While HACCP has been very effective at the post-harvest level, it must be recognized that there are multiple sources for pathogen entry at the preharvest level. Consequently, solutions will involve integrative approaches with multiple control points. It must also be realized that reduction of organisms at the preharvest level will only affect food safety if controls along the entire food production continuum are in place.

Systematic Surveillance

There is a critical need to identify the ways pathogens enter the farm environment, how they persist and spread in those environments, what “dosage” of organisms causes disease in humans, and whether on-farm acquisition of these pathogens leads to increased risks of foodborne illnesses in humans. These data may be obtained through an integrative approach of epidemiologic, clinical, and laboratory-based studies and surveillance. Currently, however, there is little “formal” pathogen surveillance in livestock prior to slaughter. This is a function of the lack of tests and the design of effective sampling strategies, among other factors. In addition, because the number of livestock animals raised for food is large, any surveillance program will be expensive. This raises the question of establishing cost benefit relationships for different surveillance programs. A systematic and effective approach to testing the burden of pathogens carried by livestock and poultry on the farm may provide important background data on pathogen reservoirs, pathogen movement, and potential controls.

Coordination: It is presumed that a great deal of surveillance data is collected in corporate contexts, but because of confidentiality concerns it is not available to researchers and decision makers. In order to take full advantage of the data resources available from farms, it is desirable to build data collection and management protocols that balance corporate needs for confidentiality with the public’s need for effective industry-wide preharvest safety surveillance.

Databases: Public databases can be valuable tools in utilizing surveillance data. However, there is currently an unmet need for this type of resource in the surveillance of foodborne pathogens. A publicly accessible database of genetic sequences from known organisms from animal, human, and environmental sources could include pertinent information for researchers and clinicians, such as details about the origins, occurrence, associated disease, and virulence of the pathogens. Such a database would require a mechanism for capturing clinical and research data and for searching data, correlating findings, and making predictions. Information about organisms that have little or no known significance to public health are worthy of inclusion, as the details of these organisms could be pertinent to investigations of future outbreaks and emerging infections. The United States does have PulseNet, which is a database of molecular fingerprints of microorganisms causing foodborne illnesses in humans, foodborne pathogens isolated from animals, and isolates from retail meat, poultry, and fresh produce. PulseNet has allowed the rapid genetic comparison of isolates to be used in outbreak analysis

and identification of the source of disease during epidemiological investigations, but access is limited to participants in the system.

Risk Assessment

Risk assessment – the systematic evaluation of the hazards and probabilities associated with pathogens on the farm – is enormously valuable to achieve an understanding of how pathogens enter into the food production continuum, to identify risk factors, and to identify measures most likely to prevent breaches in food safety. Implementation of a risk assessment can identify the data gaps that prevent adequate description of the pathogen-food-environment system and can identify priorities for managing the risks resulting from pathogens on the farm. As interventions are designed and implemented, risk assessment can be used to compare their relative merits and select the most effective techniques.

To make full use of risk assessment in preharvest food safety, a number of needs must be met. There are many data gaps in preharvest food safety that limit the usefulness of risk assessment efforts. A good risk assessment must be built on a solid base of quantitative data pertaining to the exposure to food safety hazards and the consequences of that exposure. However, very little of this type of data is available. Continuing efforts are needed to generate quantitative data on the hazards and health risks posed by pathogens on the farm. These data inputs should be evaluated with a rigor proportional to the scope of the assessment and its anticipated impacts. However, current data gaps are so numerous that quantitative risk assessments are of limited use when applied to characterize risk associated with the preharvest phase of the farm to fork continuum.

Multidisciplinary expertise is also critical to assessing risk. The complexity of the food production continuum requires the knowledge of a variety of professionals, such as environmental scientists, agricultural specialists, microbiologists, food scientists, epidemiologists, statisticians, and hydrologists, veterinarians, plant scientists, and marine biologists. There is a need to standardize the process and method of microbial risk assessment in preharvest food safety so that they may be carried out more efficiently and so the results of multiple risk assessment exercises can be compared and evaluated.

A number of pitfalls can arise in the use of risk assessment, and its application in preharvest food safety is no exception. All risk assessments are based on assumptions to some degree, and it is possible to over-interpret the results or to place more credence in

the results than the underlying data and analyses merit. Consequently, it is critical that all assumptions are based on sound scientific observations, be clearly stated, are backed by data whenever possible, and that full consideration of variability and uncertainty is undertaken in the performance of a risk assessment.

Incentives for Change in Preharvest Food Safety Practices

Like almost any industry, food production practices are entrenched, often dictated by tradition and local conditions. Change, by itself, is not easy.

There are a number of incentive concepts through which government or other food safety interests can effect change, leading industry to follow practices in pursuit of greater product safety. At their heart, all effective incentives are likely to be based on economics. For example, granting market access only to those producers agreeing to meet retailer or purchaser specifications could be a powerful tool. Consumer demand can be an incentive, too. For example, in pilot projects in Minnesota, beef and pork produced by “Good Manufacturing Practices” command a premium in stores. Large consumers, such as the McDonald Corporation, wield high-level influence on producers. These are examples of positive incentives; an economic gain is the impetus.

Negative incentives are also likely to work. Product traceability is an important negative incentive tool that confers an economic disadvantage to those producers identified as delivering contaminated products to the marketplace. Avoiding legal liability for causing illness in consumers is also an incentive for maintaining higher preharvest safety standards. However, it was a consensus of colloquium participants that positive incentives were likely to be more effective.

Impacts of Trade

Trade concerns have improved preharvest food safety practices in certain industries. There are some benefits to using safety as a value-added component in the marketing of food products. For example, in order to provide a competitive advantage to its poultry industry, Denmark has undertaken a successful program to purge *Salmonella* from its chicken farms, which now market their products as “*Salmonella* free.” The United Kingdom has begun a certification system for egg production, in which eggs can be labeled as originating from “*Salmonella* free stock.” Some companies have even implemented what they call “food safety programs” that are really intended as marketing

ploy to lure consumers to an ostensibly safer product. However, most producers and countries are reluctant to use food safety as a selling point, as it may open them up to liability and public criticism in the event of any real or perceived safety breach. Furthermore, consumers have a built-in expectation of safe food. Moreover, the added preharvest and post-harvest safety steps required to confidently proclaim a product “safe” are expensive, often putting the product at a price disadvantage when compared with less rigorously protected products. For many products, when consumers recognize a trade-off between product safety and cost, the less expensive item will prevail. Hence, the benefits of using safety as a product value are strongly dependent on the commodity at hand and the pathogen in question.

SURVEYING THE LANDSCAPE AND IDENTIFYING THE PROBLEMS

Not only is there a wide variety of food products, but food safety research is complicated by the range of pathogens on the farm and the range of organisms associated with each food product. This makes it more difficult to target specific organisms with limited resources. While animal health and production is affected by some of these organisms, priority must be given to those foodborne pathogens of highest public health impact.

With public health in mind, there may be a number of ways to rank safety concerns, including prioritizing the risks posed to susceptible individuals, the risks posed to the greatest number of people, the risks of the most severe health consequences, the risks posed by various products, or the risks based on monetary values. The science behind development of indices to rank the degree of risk posed by multiple agents is in its infancy, and there are no generally accepted tools presently available in this regard.

The Pathogens: Sources and Controls on Their Growth

The inventory of foodborne pathogens is extensive, and different lists of pathogens can be derived for every type of concern in food safety. The list of pathogens responsible for the most frequently diagnosed diseases, for example, is different from the list of those pathogens that cause the most severe illnesses,

and also from the list of those that most frequently affect susceptible individuals in the population. Each of these lists is informative in its own way and can guide efforts toward the most critical food safety issues. However, in considering food safety at the production level, as well as routes of contamination of food products, it is instructive to divide pathogens into broad categories that share many of the same properties.

Viruses: Currently recognized foodborne viruses are known to originate from human feces. Although certain viruses are now thought to cross species barriers readily, the importance of these animal viruses to food safety is not known.

With respect to managing food at the preharvest stage, pathogenic viruses are most important in the production of produce and shellfish. Produce may become contaminated by a number of routes, either by direct contact with infected individuals or through exposure to contaminated water. Hence, on-farm hygiene is an important issue when it comes to managing virus contamination of produce. Appropriate toilet and washing facilities are necessary to prevent direct viral contamination of produce, and careful management of human wastes is critical to preventing contamination of the water used for irrigation and washing. This problem is exacerbated since the practice of keeping workers who are ill or who are shedding enteric viruses from working on harvest production lines is very difficult to enforce. Given that such workers are likely to have low incomes, taking a sick day is a strong economic disincentive.

Pathogenic viruses are introduced to shellfish primarily by exposure to human waste effluent released to the waters in and around shellfish beds. Managing the flow of human wastes in watersheds where shellfish are harvested is critical to ensuring that viruses do not taint shellfish supplies.

Parasites: Parasites implicated in foodborne illness include such protozoan organisms as *Cryptosporidium*, *Cyclospora*, *Giardia*, *Taenia solium*, *Microsporidium*, *Trichinella*, *Sarcocystis*, and *Toxoplasma* species. The original source of these agents is human and animal fecal matter. The hardiness of some of these microbes enables them to survive in the environment, particularly in water, for great lengths of time. Not all parasites are waterborne, however. Other reservoirs available to them include feces of livestock animals and indigenous wildlife. Livestock raised outdoors can acquire parasites from contaminated soil and water, potentially compromising food safety. As consumer concerns for animal welfare drive increasing demands for free range meat and poultry, it is possible that preharvest

problems related to parasites acquired from feral animals or their feces in the pasture will increase as well.

Bacteria: Like viruses and parasites, the ultimate sources of most bacterial foodborne pathogens are humans and animals. However, the problem of bacterial pathogens is complicated by the fact that many of these organisms can replicate in the environment. Furthermore, many foodborne bacteria are ubiquitous, particularly on farm and in aquatic environments. Hence, bacteria, once introduced to a food production environment, may proliferate, making them difficult to control.

The severities of bacterial foodborne diseases vary greatly, depending on characteristics of both the pathogen and the host. Clearly, vast differences exist between different classes and species of pathogens, but important differences also exist even between very closely related subspecies of pathogens. Bacteria of the same species, but of differing strains, subtypes or serotypes, have profoundly different effects on human health. Characteristics of the host that affect severity include age, immune status, and nutritional status, among other factors.

As opposed to the processing and packaging stages of food production, food in the preharvest stage is more vulnerable to contamination because of the variability of the environment and our inability to control it. Many foodborne pathogens originate from human and animal fecal waste, although some pathogens, such as *C. botulinum* and *Listeria monocytogenes*, are common soil or environmental inhabitants. Numerous different secondary sources of pathogens include water, soil, ice, wildlife, and manure contaminated with pathogenic microbes.

What Promotes or Reduces Pathogens numbers in Food on the Farm? The number of pathogens in a given farm environment is determined by a complex interplay of factors. Promoting factors include animal density, the use of contaminated livestock feeds, amenable climate, inputs of contaminated water, unsanitary handling of water and wastes, contact and commingling between infected animals and the uninfected, and the recycling of farm wastes. The commensal microflora of livestock may also play a role in promoting or inhibiting pathogen proliferation on the farm, but the exact role is not well understood.

Factors that can reduce on-farm burdens of pathogens include sanitary handling of water and waste, decontamination strategies, vector control, livestock vaccines, disinfection programs, the use of antimicrobial therapies, and, possibly, the use of probiotic therapies.

Foodborne Pathogens in Industrialized Nations and the Developing World: The problem of pathogens at the preharvest stage of food production is a complex one, affected by farming practices, geography, economics, and cultural factors. These factors differ in many ways between industrialized and developing nations. The former are characterized by relative resource wealth, the ready availability of clean water, and the dominance of industrial agriculture, while the latter are relatively resource poor, often lack clean water supplies, and have high numbers of small-scale or subsistence farms that generate both produce and livestock.

The Ecology of Foodborne Pathogens

Pathogen Eradication: Foodborne pathogen eradication is not an appropriate goal for most preharvest food safety programs. Pathogens can never be eliminated from the farm because they are ubiquitous in the environment, especially on farms. Despite the implementation of any number of rigorous, comprehensive strategies to control pathogens, viruses, bacteria, and parasites will always persist. It is possible that overly aggressive efforts could lead to unintended effects by encouraging the growth of extant or new pathogens. A more tenable goal is achievement of target prevalence or target levels of pathogens. These goals would be set based on estimates of risk and what degree of risk is considered acceptable. Considerable baseline data will be needed before determination of target levels can be addressed. In order to ensure they are reasonable and defensible, pathogen target levels need to be directly linked to public health goals. To do this, reliable measures of the infectious dose of pathogens required to elicit disease (if these parameters can be determined) would be extremely helpful. Establishment of infectious dose is a clear research need, albeit a different goal.

Reducing Pathogens on the Farm: the Solution? Disagreements persist about the relationship between reductions in the prevalence of pathogens at the preharvest stage and the incidence of foodborne illness. For some combinations of organism and locale, a correlation between disease reduction and pathogen reduction has been observed. For example, reductions in the numbers of *Campylobacter* in Icelandic poultry were accompanied by corresponding reductions in the number of *Campylobacter* infections in consumers. A reduced incidence of human disease caused by *Salmonella* occurred at approximately the same time that reductions in *Salmonella* in Swedish poultry occurred.

Although instances of preharvest safety measures being associated with reductions in foodborne illness have been reported, a definitive causal relationship

between reducing the burden of pathogens on the farm and reducing outbreaks of disease has never been conclusively demonstrated for many pathogen/disease combinations. This may be in part because there are other points within the food safety continuum for pathogen introduction beyond the preharvest phase. In addition, many foodborne outbreaks have no identified source. Another possible cause may be that the scientific community has not yet tried to link preharvest control strategies to definitive public health goals.

The handling of products in batches after processing could also explain why reducing pathogens on the farm does not always translate into reduced numbers of infections. Cross-contamination within lots of produce or meat may mask the benefits of careful preharvest practices due to the effects of lot mixing or commingling, whereby one contaminated batch can go on to contaminate an entire lot. This may be particularly important for foodborne pathogens like *E. coli* O157:H7 where the infectious dose is quite low (perhaps as low as 101 cfu). Finally, some pathogens cause disease at such low doses (e.g., human enteric viruses and EHEC strains) that pathogen reduction may not be sufficient to decrease the incidence of disease. Only pathogen eradication will eliminate illness. Because pathogens can persist in the environment, and may be carried by animals other than those used for food, such eradication will be difficult to impossible to achieve for many important foodborne pathogens.

Indicators v. Direct Pathogen Detection: Microbiological indicators are microbes or microbial products that, when found in a food or food environment, can indicate a potential risk of foodborne pathogen contamination. Effective indicators can be applied in any of three distinct uses in managing food safety: (1) as the trigger of a feedback loop to improve food management, (2) as a criterion for determining the immediate disposition of a product, and (3) for research into the efficacy of new control methods. The commonly used bacterial indicators include coliforms, fecal coliforms, members of the family of *Enterobacteriaceae*, and *E. coli*. While these are routinely used to monitor environmental (coliforms and *Enterobacteriaceae*) and fecal contamination (fecal coliforms and *E. coli*), they are far from ideal. In fact, for certain pathogens, there is no significant relationship between the presence of fecal indicator bacteria and presence of the pathogen, as is the case for viral contamination of shellfish and their harvesting waters. In the past, most techniques for detection of microbiological indicators have relied on cultivation in selective media, and while easy and inexpensive, these methods still take 24 hours or more to complete. In some instances, alternative indicators, including chemical and serological tests, have been developed. Despite the availability of a number of

microbial indicators and serological tests, alternative indicators that are more robust, have better relationships to pathogen presence, and are easier and quicker to perform are still needed.

An alternative to the use of microbiological indicators is direct detection of pathogens in the sample matrix. These methods, like indicator methods, have been historically based on cultural detection methods, but newer approaches, based on detecting the DNA or RNA of the pathogen, and further characterizing it using genetic fingerprinting methods, have been developed recently. For example, the polymerase chain reaction (PCR) provides a means by which to amplify a specific DNA sequence, perhaps obviating the need for lengthy cultural enrichment steps, thereby being faster than cultivation-dependent methods. With real-time methods PCR can have at least semi-quantitative endpoint. However, PCR is not the panacea that was initially anticipated, as the method is limited by the need for very small amplification volumes, and most samples contain inhibitory compounds (seen in particular for fecal, food, and environmental samples) that reduce PCR assay sensitivity and specificity, leading to false negative and/or false positive results. There clearly is a need to address these issues before PCR is routinely used to screen directly for pathogens in the preharvest environment.

Logical extensions of molecular amplification technologies are gene chips and biosensors; the relative speed of these techniques could allow real-time identification of safety problems on the farm. While being predominantly developed for post-harvest food safety and for food security, it would make sense to move these technologies into the preharvest arena in the near future.

Preharvest Determinants of Pathogen Load: Many pre- and post-harvest factors are likely to affect pathogen load in animals and produce. Factors, such as seasonal variability, changes in temperature, and precipitation, probably influence the abundance and dispersal of pathogens. Pathogen loads can also be affected by the movement of animals and supplies during production, as might be the case for seeds, bedding, feed, or through livestock. Worker sanitation and farm hygiene practices also can influence the persistence and dispersal of pathogens on the farm. For instance, pathogen-contaminated dust has been implicated in the deposition of harmful microorganisms directly onto food products or in the production environment.

Other preharvest determinants of pathogen load are likely to be specific to each type of agricultural product. The introduction and proliferation of pathogens

during production of meat is particularly fraught with numerous entry points where care must be taken to prevent pathogens from entering the food supply. Some recognized risk factors related to pathogen carriage include:

The age at which new animals (whether they are born on the farm or transported there) are first exposed to pathogens.

- The quality and type of feeds consumed.
- Animal health status.
- Exposure to antibiotics.
- Exposure to wildlife, which may carry pathogens.
- Exposure to livestock animals that are shedding pathogens.
- Climate and season.
- Shipping of animals.
- Hygiene conditions in lairage and at the entry of the slaughter plant.
- Environmental hygiene, including effluent management.

These factors probably are interactive and not only predict the likelihood of exposure to foodborne pathogens, but also affect pathogen load in food animals.

Preharvest factors that determine pathogen load in fresh produce are just as important. It is known that weather plays a prominent role, and damage from bruising or rotting can encourage establishment of human pathogens by providing a nutrient rich environment for pathogens to grow. Water can be another source of pathogens. The irrigation method, if used, is an important determinant. Sprayed water comes into contact with plants, and spraying equipment can spread pathogens if the equipment is contaminated, while water in irrigation ditches does not necessarily come in contact with the plant. Finally, since fresh produce is frequently harvested by hand, factors associated with human handling come into play.

For fish and shellfish, the quality of the water in which they are grown is paramount in determining pathogen load in the final product. For environmental *Vibrios*, the microbiological quality of harvesting waters is influenced by season, as well. The use of antibiotics and recycled fish products as feed can also play roles.

Diet: Diet is a determinant of the number and types of pathogens carried in the intestines of livestock. Regional differences in the diets of cattle have been shown to result in corresponding differences in the pH of the fluid in the rumen of cattle. This difference in pH may lead, in turn, to marked differences in the microbial flora of the rumen. In another example, the use of

coarsely ground feeds has been shown to reduce the incidence of *Salmonella* in swine. Although a significant research area, there is little conclusive evidence about the particulars of the interactions between animal feed and pathogen populations. To date, no specific diet change has been found to predictably alter the presence of pathogenic flora in livestock intestines. A consistent relationship between the typical cattle feeds and cattle gut microbial flora has been sought, but remains elusive.

The use of probiotics – therapies that promote the growth of beneficial microbes in the gut – holds promise for controlling pathogen carriage and shedding in livestock. Some studies have indicated that the use of probiotics can drastically reduce pathogen carriage. Questions remain about the exact microbial composition of commercial probiotics and competitive exclusion products (see below), about how well they have been tested for safety, and the mode of action of these mixtures. It is not known how most probiotics affect enteric commensal bacteria. More field studies are needed before probiotic techniques can be applied dependably. Also, there is some evidence to suggest that once probiotics are discontinued, pathogens may become readily reestablished, meaning that their use may be required over the life of the animal, perhaps at considerable cost.

The use of probiotics as “competitive exclusion” agents entails the use of a mixture of microbes to supplant pathogen populations in the gut. As the routine use of medically important antibiotics in livestock is phased out, alternative pathogen management strategies, possibly including competitive exclusion, will be needed. One competitive exclusion product has been approved by the FDA and consists of a defined culture of microorganisms.

Fundamental research is also needed to identify the role of normal intestinal microflora before scientists can develop effective competitive interactions between pathogens and therapy organisms. These normal microorganisms are believed play an important role in the health of animals. Interactions between these microbes and the mechanisms of how they promote good health, coupled with an understanding of how the normal microflora regulates or excludes foodborne pathogens, are important emerging areas of research that need to be addressed.

Seasonality: In many preharvest environments, there is a marked seasonality to the occurrence of foodborne pathogens, but the exact seasonal relationship varies from pathogen to pathogen. Swine-related *Salmonella* exhibits strong seasonality, as does *E. coli* O157:H7, which has been shown to have a higher animal prevalence during July, August, and September in

the Northern Hemisphere. Variability in pathogen prevalence with the time of year may be due to a number of factors, including precipitation rates, temperature fluxes, or the ability of the pathogen to proliferate in the environment. Seasonality of production practices may also be responsible in some cases; practices that are carried out only at certain times of the year may trigger changes in pathogen populations. For example, harvest time is a seasonal event that can affect the number of pathogens on the farm.

However, the incidence of human foodborne disease does not always track the seasonal changes in pathogens on the farm, although *E. coli* O157:H7 infections are higher during the warm summer months. A number of post-harvest events can impact pathogens present in food and may mask seasonal fluctuations in foodborne contamination. Globalization of food production may also hide subtler seasonal effects. Since fruit and vegetables on supermarket shelves come from all over of the Globe, and seasonal effects can vary significantly between areas of different climate, disease incidence is not always predictable. Research is needed to identify the effects of climate and geography on the seasonality of foodborne pathogens on the farm.

Microbial Interactions

Unintended Costs of Eliminating Pathogens: Deleterious effects have never been documented in the wake of eliminating a foodborne pathogen from the preharvest environment, but the potential exists for animal health risks resulting from such an action. For example, elimination of a given pathogen could open an ecological niche to another, more harmful pathogen. A number of pairs of pathogens are known to share nearly identical ecological niches, making them potential candidates for this type of phenomenon. For instance, it has been proposed that the *Salmonella pullorum* eradication program in chickens led to the proliferation of its close relative *S. enteritidis*, a severe human pathogen.

Predicting Emerging Pathogens: Microbes are constantly evolving – changing in subtle and radical ways to adapt to new environments and to shifts in their normal environments and, in the case of pathogens, to new hosts. As a result of this evolution, new pathogens and diseases are continually being brought to the attention of the medical community. New foodborne pathogens, too, are emerging constantly, and it is nearly impossible to predict what sort of pathogen will arise and in what context. Despite these sources of uncertainty, certain factors that have roles in the emergence of new pathogens can be identified.

Introduction of new antibiotics and the subsequent evolution of pathogen resistance to those antibiotics will impact emergence. Likewise, changes in production practices that alter such parameters as growth rate and stocking density are likely to select for new agents or changes in the sites of pathogen colonization of animals. For example, the shift to higher stocking density of pigs and the move to indoor all-in-all-out facilities have led to the emergence of *S. choleraesuis* as a respiratory pathogen. Climate change also may have a role in the emergence of foodborne pathogens in the future. With the onset of irregular weather patterns and changing regional temperatures, the ranges of both disease vectors and pathogens will probably shift, introducing organisms to areas where they have not been seen before and altering other pathogens as they struggle to persist in their original habitats.

As quality of life improves around the world, it is likely that national populations will age and the numbers of pathogen-susceptible individuals will grow. This could result in increased incidence of foodborne diseases and could provide conditions for new foodborne pathogens to take advantage of these more vulnerable groups.

New diagnostic tools and improved surveillance are continually revealing additional information about foodborne pathogens. In the future, it will be important to distinguish between the improved resolution afforded by these new resources and the apparent acceleration of pathogen emergence.

Biological Security on the Farm

In recent years, terrorism has become more visible around the world, striking close to home even in developed nations. In the wake of terrorist acts, authorities have voiced concerns about the security of the world's food supplies. The point of origin of food, the farm, is seen as a vulnerable target in the farm-to-fork supply chain. Biological threats to food are particularly worrisome, as their effects may be felt beyond the site of the original attack, in supermarkets and homes where any number of people could be sickened, or on farms surrounding the targeted area that are vulnerable to the spread of a contagious plant or animal pathogen. An attack on the food supply does not necessarily have to sicken people to have an effect; simply interrupting the food supply would be enough to spread terror in a targeted nation and impact its economy.

A determined enemy would find most farms vulnerable to terrorist attack. Currently, there is little that can be done to stop someone with financial resources and

malevolence from targeting the world's food supply during the preharvest stage. Although some measures have already been put into place to improve farm security, farmers, scientists, public health officials, and regulators should continue to prepare themselves to manage the consequences of such an attack. The large number of differences in preharvest production practices makes management of food bioterrorism all the more difficult. For instance, because of the widespread use of indoor housing in the pork and poultry industries, introduction of foodborne pathogens might be more difficult here than for free range animal production sites.

Security-Sensitive Features of the Preharvest Stage:

Events and locations on a farm that are most sensitive to targeting by ill-intentioned persons vary between industries and between products. However, certain critical steps are common to many farming scenarios. For example, the introduction of new livestock on the farm is a critical point in farm security.

Maintaining the microbiological quality of livestock feed, water sources, and circulating air is critical to on-farm security, as is the cleanliness of the objects with which livestock and crops come into contact. Barriers to wildlife can help prevent the introduction of pathogens from outside the farm. Finally, the movement of animals off the farm is highly security-sensitive and needs to be closely monitored.

Security Needs: Ensuring security of food in the preharvest environment requires an extraordinary, coordinated, and costly effort by farmers, regulators, and scientists. Such an effort is clearly many years away from becoming reality. However, certain steps can be taken immediately that would not only improve farm security, but would also have the effect of reducing the load of pathogens on the farm. Some changes are already being made in an effort to improve on-farm security.

Adherence to good management and quality assurance practices on the farm would help to prevent pathogen distribution, whether they were introduced deliberately or otherwise. These programs primarily target animal pathogens, but will likely help control human pathogens that are carried by animals as well. Careful management would include record keeping, training of farm personnel in food safety and security related issues, and careful cleaning of livestock buildings between groups of livestock. Simple measures, such as requiring farm workers to change their boots between pens, help to improve security. Ensuring security of the animal feed supply while it is on the

farm is also important; certificates of origin should be maintained and feed should be traceable to its source. Careful record keeping and the ability to track and trace back will be important components for containment of a terrorist attack were one to occur.

Regulatory bodies should also shoulder some of the burden for improving farm security by fostering enhanced accountability among producers for breaches in food safety. Quantitative and qualitative pathogen surveillance is needed. Emergency preparedness plans need to be put into place at the producer level and at county or regional levels. In the U.S. and many other countries, the realm of on-farm security is not clearly the dominion of a single agency, and the details of which regulatory body should bear the costs associated with increased surveillance, emergency preparedness, and certification programs has yet to be resolved.

Research can play a role in on-farm security by improving the efficacy of safety interventions and developing novel tests and prevention regimens. In light of the increased threat of deliberate pathogen introduction, many of the hygiene interventions currently in place to prevent the spread of pathogens on the farm require more thorough validation. Rapid diagnostic tests are needed, particularly simple, field-based technologies that can be performed "truck-side" or in other similarly uncontrolled circumstances. Livestock vaccines are needed to prevent the spread of enteric pathogens, as are statistical approaches to aid in the design of effective pathogen surveillance programs, particularly when looking for so-called "rare" events hidden within the usual foodborne disease burden, as might be the case with intentional acts of contamination.

RESEARCH NEEDS

Although there is some understanding of the dynamics of pathogens in food production environments, comparatively little is known about preharvest food safety as it relates to human health. Research efforts are essential in validating intervention strategies, developing tools for pathogen detection and enumeration, determining the impacts of chronic and mild foodborne illnesses, exploring the uses of functional genomics in preharvest food safety applications, understanding the microbial ecology of pathogens on the farm, and evaluating the production costs associated with preharvest safety measures.

Intervention Strategies

A number of procedures are used to prevent the introduction and proliferation of pathogens on the farm. Often these interventions are put into place without a thorough understanding of their efficacy or when their use is likely to have the greatest impact. Many interventions, although intuitively appropriate for managing pathogens, are either ineffective or too costly to justify the small return in reduced pathogen prevalence they yield. Research is needed to evaluate existing and alternative intervention strategies for their efficacy and for their impacts on the farm environment. In particular, alternative management strategies that employ proactive preventive elements should be closely studied. For example, livestock specifically bred for disease resistance or for their inhospitality to human pathogens could be used in managing pathogens on the farm with minimal effects on the environment. However, to date, such genetic approaches really are basic research questions of approach and application. Such approaches should be investigated.

The Critical Control Points (CCPs) for reducing the prevalence and load of pathogens on the farm would serve as natural targets for designing new interventions. In most cases, these potential control points have yet to be identified for the various types of production environments or for each pathogen of concern. This information would be highly valuable. An important component of a HACCP-like control approach would be the development of effective, inexpensive, rapid sampling and measurement tools to facilitate identification of out of specification CCPs. To date, these tools are sorely lacking.

Detection and Enumeration

Tools currently available for pathogen and indicator detection largely rely on the ability to grow these organisms in the laboratory. Although these tools have been valuable so far in understanding microorganisms on the farm, new molecular approaches that do not require cultivation, but instead employ the detection of either genes or proteins for positive identification, are needed. Some of these are commercially available, but have not been validated for the preharvest environment. To bring these methods to the farm, they will need to be simple, fast, inexpensive, and robust. They will also have to be validated against existing gold standards, which to date, are cultural methods. Many of these methods have been used to detect the presence or absence of a pathogen, and modifications will need to be developed to make these assays more quantitative in nature. Molecular tools to detect and enumerate disease-causing organisms, especially

viruses and protozoa that are found on the farm and in food, are particularly necessary since these organisms are particularly difficult if not impossible to culture with current technology. Ideally, tools should be developed to assess pathogen viability and virulence. New technologies like gene chips and biosensors hold particular promise as rapid and sensitive tools for detecting changes in pathogen occurrence and should be explored.

Research also is needed in identification and development of indicator organisms. A systematic study is needed to evaluate indicators currently used with respect to their ability to predict pathogen presence in a given sample and their correlation to some of the newer water and foodborne pathogens of concern today. It is likely that new indicators need to be identified. The relationships among indicator organisms, pathogen presence, and ultimately, public health outcomes also must be explored.

Impacts of Chronic and Mild Foodborne Diseases

Diseases associated with foodborne pathogens run the gamut in severity, from mild, flu-like syndromes to acute illnesses with effects on multiple organ systems. The frequency of foodborne diseases also varies greatly. Some illnesses occur with a high frequency (gastrointestinal viruses, for instance) striking consumers on a regular basis, while others are rare and sicken few people every year. Historically, relatively rare diseases that are associated with high mortality have captured the attention of the public and lawmakers, resulting in an emphasis on these types of disease in funding and, hence, in research. For example, Bovine Spongiform Encephalopathy (BSE) is a rare disease, but when it occurs, the mortality rate is high. Consequently, the impacts of mild and chronic infections have often been overlooked, even though morbidity and economic costs associated with these illnesses may be high. Links between foodborne disease and chronic illness need to be explored further. The connection certainly exists for some pathogen/disease combination, and it may exist for others as well. It still is uncertain, for example, whether the correlation between the presence of *Mycobacterium avium* spp *paratuberculosis* and Crohn's disease is causal in nature. All foodborne illnesses have societal costs, regardless of whether they are lethal or not. Research is needed to evaluate the impacts of all foodborne illnesses, particularly common, relatively mild diseases, in terms of their effects on the quality of life and on economics. Metrics, like Quality Adjusted Life Years (QALYs) and Disability Adjusted Life Years (DALYs), which quantify the decrease in quality of life or the number of days lost to illness and death from disease, respectively, are

important tools to determine the severity of foodborne illnesses and their true impacts on society. They also provide a common quantitative measurement by which to compare the impacts of disparate illnesses and determine which illnesses merit more attention and resources. The challenge will be to find ways to separate out preharvest from post-harvest issues with respect to measuring specific public health outcomes. For instance, CDC FoodNet data shows a decrease in almost all foodborne illnesses in the U.S. over the last several years; however, what proportion of these decreases are due to preharvest controls, and what proportion are due to post-harvest controls, and what proportion are associated with inherent variation in disease rates remains unknown.

Functional Genomics

Functional genomics, the use of an organism's genome sequence to determine the function of every gene and its products, is a promising tool for studying pathogens on farms, but little has been done yet to harness these technologies in preharvest food safety. Functional genomics could possibly be applied to trace the source of a pathogen, predict pathogenicity of a given organism, identify novel pathogenic mechanisms, determine the stability of a pathogen population over time, and investigate the co-evolution of commensal organisms and pathogens.

Microbial Ecology

Pathogens do not exist in a vacuum. On the contrary, they are part of the community of microbes found in animals, on farms, and on fruits and vegetables. Each member of the community contributes to the ecology of the habitat, and altering the numbers of one microorganism is likely to impact other members of the ecosystem. The microbial population of the average mammalian intestinal tract harbors on the order of 10^{14} bacterial cells. The interaction of these microbes with their habitats, be it the intestinal tract or the barnyard, dictates the outcome when a foodborne pathogen is introduced into that habitat. Interventions to minimize or eliminate pathogens in crops and livestock will have far-reaching implications for the balance of the microbial community and may leave the animal more susceptible to colonization with other foodborne pathogens. Research is needed to evaluate interactions between the members of the microbial population and with their environments and the effects of interventions on the other microbes present on the farm and in the animal. It may be that certain pairs of microbes are clearly linked in their prevalence. For example, the possibility that interventions to minimize

a given pathogen actually have the effect of increasing risks from another pathogen should be explored.

The question of how food safety interventions on the farm affect commensal organisms is particularly interesting. Comparatively little is known about commensal bacteria, but we do know that a healthy commensal microbial flora contributes to the health of many species. As part of the evaluation of commensal bacteria, it is important to define what a commensal bacterium is and what constitutes the "commensal microflora." If the elimination of a given pathogen affects commensal organisms at all, it would be beneficial to producers, public health officials, and consumers to uncover the details. Understanding these interactions could lend more information to the struggle to control foodborne disease.

Other pressing research questions with respect to pathogens and commensals include:

- Does the routine use of antibiotics in livestock change the animals' microbial flora such that new, more virulent pathogens become a problem? Will the removal of antibiotic growth promoters from the diets of livestock animals lead to greater or lesser risk of carrying foodborne pathogens?
- Do some pathogens only cause disease in the presence of other organisms? If so, what are the other organisms and can they be managed effectively?
- When a pathogen changes physiologically, how do the surrounding organisms respond?
- How do microbial interactions within communities, for example quorum sensing, encourage the growth of pathogens? How can we turn this to our advantage in managing pathogens?
- How do food safety interventions affect microbial population distributions and the movement of genes among microbes?
- How biased are studies that focus on a single organism? Are single organism studies futile in light of the impacts of community dynamics on pathogen populations?
- What are the likely infectious doses for different in different groups of consumers?

Costs of Preharvest Safety

Preharvest food safety measures incur costs to the producer, but the burden of these programs and their

effects on the future of food products are poorly understood. Costs associated with implementation of food safety programs usually differ based on product type and producer volume, and this needs to be investigated. Furthermore, in the long run, increased costs to producers and processors are almost always passed on to the consumer, so consumer willingness to pay for improved food safety must be considered as well. Food safety interventions should be invoked as a benefit to producers, rather than one with punitive outcomes.

COMMUNICATION AND EDUCATION

Preharvest food safety has been detached from public health, but the reality is that safe (or unsafe) food directly impacts public health, and food safety professionals must recognize that their ultimate goal in improving the safety of the food supply is to positively impact public health. Consequently, it is critical to be able to convey the facts about managing pathogens on the farm clearly to a wide audience. Moreover, the field is in need of professionals from a wide variety of disciplines, and recruitment and training are going to be pivotal to maintaining progress in improving the microbiological integrity of food products.

Consumers

Although consumer perceptions about preharvest food safety vary from product to product, their influence on the food industry can be profound. These perceptions are shaped by many forces, most notably by inputs from the media and the internet, sources that are not always correct. Moreover, messages available from the many broadcast, print, and electronic sources can be conflicting and confusing, given that there is no central source of reliable information on the subject, and few consumers know enough about science and food production to distinguish good information from bad. The general consensus among the public seems to be that the information provided by the government, politicians, and scientists is flawed.

Scientists and governments need to do a better job of informing the public on food safety matters. Special communications programs that convey nonbiased scientific information in an intelligible format to the public and to the media are needed. The issues can be contentious, so information needs to be presented in a neutral environment where the public, government, and scientists can come together. Universities may serve as appropriately neutral hosts for information dis-

tribution, and university extension faculty could function as mediators between producers and the public. Interestingly, as national communication programs in food security are being launched, these programs may be able to be used to convey information on general food safety, too.

Training Scientists

As the global population climbs and agricultural methods become more intensive, international trade in food becomes will become even more prevalent. It is likely that the importance of preharvest food safety also will grow as a consequence of these developments. Now and in the future, trained professionals are needed for carrying out the work of ensuring the safety of the food supply while that food is produced and held on the farm. Opportunities abound in this area, including employment openings in research, diagnostics, epidemiology, public health, technology development, preventive veterinary medicine, regulation, surveillance, and agricultural extension.

It will be critical to attract sufficient numbers of suitably qualified people into the field of preharvest food safety in order to have a critical mass of professionals to carry out the work of pathogen management. Aside from the usual need for veterinarians and agricultural scientists, individuals at work in improving preharvest food safety will also need training in such diverse fields as engineering, ecology, biometrics, statistics, and microbiology. Collaborations among professionals in these fields will be necessary to make the best progress; for example, agricultural experts will need to be in contact with engineers and molecular biologists in development of cutting edge biosensors and gene chip technologies for diagnostic use on the farm.

In recruiting people into food safety training, it will be necessary to demonstrate the rewards of working in the field, including the benefits of these careers, future prospects, and job security. A comprehensive effort by government may be necessary to attract sufficient numbers of professionals to the field. Fellowships and student loan forgiveness may also be advisable.

In educating students who will go on to careers in food production and preharvest food safety, it will be critical to include training in modern methods, including the tools of biotechnology, epidemiology, statistics, food hygiene and public health. Summer internships in preharvest food safety in the fields of public health or animal science could enhance students' knowledge base and would expose them to the breadth of opportunities available. Communication is also a key element of this field, as research and development at the heart of

preharvest concerns ultimately means a great deal to the public-at-large. In universities, it is recommended that more links be forged among communication programs and agriculture, food science, and veterinary and human medicine programs in order to improve the science communication skills of new food safety graduates.

RECOMMENDATIONS

Many of the preharvest food safety interventions currently in use have not been evaluated with respect to their impacts on public health. Research is needed to validate these approaches and to develop new interventions based on preharvest critical control points.

- Preharvest food safety priorities and targets should be set to specific public health outcomes.
- Studies clarifying the relationship between preharvest pathogens and public health should be initiated.

A publicly available database of genetic sequences from known or suspected foodborne pathogens is needed. While the, PulseNet database, may serve as a preliminary model, it is not widely available to researchers and is limited to data from North America.

- Creating a readily accessible international database is recommended.
- Among other things, such a database would allow research on emergence and the consequences of infection.
- The database should include mechanisms for data capture, data search, correlating findings, and making predictions.

Studies need to be performed to quantify the relationship between pathogen load and product contamination.

- Effective sampling strategies must be developed to maximize the value of microbiological testing for contamination.
- Rapid and inexpensive methods should be developed to quantify pathogen loads in the preharvest production environment

New and improved tools should be developed for detection and enumeration of pathogens on the farm.

- Microbial indicators are needed that more accurately reflect health risks due to fecal contamination on the farm.
- Rapid molecular tools like gene chips and other cutting-edge technologies like biosensors need to be harnessed in detection of on-farm contamination.

Well-designed longitudinal cohort studies are needed to identify risk factors associated with the contamination of produce and livestock products, and the persistence of human enteric pathogens in the preharvest production environment.

The importance of microbial community interactions on pathogens in preharvest environments is little understood and needs to be investigated more fully.

- The response of the community of gastrointestinal microbes to specific interventions should be measured to document adverse changes in pathogen abundance and diversity.
- The effects of preharvest controls on commensal microflora also need to be studied in detail.

There is a need to develop risk assessments specifically targeting preharvest food safety risks.

Guidelines for the implementation of on-farm “best management practices” are needed, to minimize the contamination of livestock and produce with enteric pathogens that cause disease in humans.

Define specific criteria for measuring the efficacy of preharvest intervention strategies.

Due to conflicting available information, the public remains relatively ill-informed on the subject of pathogens on the farm.

- The public needs to be educated to understand that “zero risk” is unattainable.
- The public needs basic education in food production practices so that they understand the complexities of preharvest food safety.
- Regulators, scientists, and producers need to make a more concerted effort to inform the public about on-farm food safety and security measures that are already in place and about future strategies that might be effective.

Probiotic therapy and competitive exclusion approaches may prove highly valuable in the struggle

to contain pathogens in livestock, but they require extensive testing before they can be endorsed for widespread use on farms.

- The exact microbial composition of probiotics and competitive exclusion products needs to be specified by manufacturers.
- The safety of these products, particularly for long term use, needs to be thoroughly studied.
- The impacts of probiotics and competitive exclusion products on the commensal communities of the animal gut needs to be explored.
- The benefits of livestock vaccination programs for the prevention of human illness need to be evaluated. ■

REFERENCES

Centers for Disease Control and Prevention. <http://www.cdc.gov/foodnet> and <http://www.cdc.gov/pulsenet>

FDA/CFSAN. 2002. Foodborne Pathogenic Microorganisms and Natural Toxins Handbook: The "Bad Bug Book." Food and Drug Administration/Center for Food Safety and Applied Nutrition, Washington, D.C.

Institute of Food Technologists (IFT). 2002. Emerging microbiological food safety issues: implications for control in the 21st century. IFT Expert Report, Chicago, IL, pp. 1-107.

Institute of Medicine. 1998. Ensuring Safe Food from Product to Consumption. National Research Council, National Academy Press, Washington DC.

Mead, PS, L Slutsker, V Dietz, L McCaig, J Bresee, C Shapiro, PM Griffin, and RV Tauxe 1999. Food-related illnesses and death in the United States. *Emerg. Infect. Dis.* 5: 607-625.

MMWR. 2003. Hepatitis A outbreak associated with green onions at a restaurant- Monaca, Pennsylvania, 2003.

Torrence, ME and RE Isaacson (eds). 2003. Microbial Food Safety in Animal Agriculture: Current Topics. Blackwell Publishing Company, Ames IA 50014.

U.S. Food and Drug Administration, U.S. Department of Agriculture, Centers for Disease Control and Prevention. 1998. Guide to minimize microbial food safety hazards for fresh fruits and vegetables. <http://vm.cfsan.fda.gov/~dms/prodguid.html>.

