HERA

Human and Ecological Risk Assessment

An International Journal

Special Issue:

Occupational Risk Assessment

James T. Wassell
Guest Editor

A. John Bailer
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Table of Contents

SPECIAL ISSUE:
Occupational Injury Risk Assessment

James T. Wassell, Guest Editor
A. John Bailer, Guest Editor

Perspective:

Occupational Injury Risk Assessment: Perspective and Introduction
by Linda Rosenstock and Nancy Stout 1255

Debate/Commentary:

Injury Risk Assessment for Occupational Safety Standards
by J.F. Martonik, E.A. Grossman, and C.P. Gordon 1259

Comparing Injury and Illness Risk Assessments for Occupational Hazards
by A. John Bailer, Leslie T. Stayner, William Halperin, Laurence D. Reed, and Tom Seymour 1265

Probability Models of Occupational Injury
by James T. Wassell 1275

A General Framework for Prioritizing Research to Reduce Injuries and Diseases in Mining
by Russell Levens 1285

Invited Papers:

I. Methodology

Lifetime Risk of Fatal Occupational Injuries Within Industries, by Occupation, Gender, and Race
by John R. Myers, Suzanne M. Kisner, and David E. Fosbroke 1291

Estimates of Lifetime Risk of Occupational Fatal Injury from Age-specific Rates
by K. See and A.J. Bailer 1309

Years of Potential Life Lost Due to Occupational Fatal Injury in the United States
by Stephen J. Gilbert, A. John Bailer, and Leslie T. Stayner 1321

Identifying Populations at High Risk for Occupational Back Injury with Neural Networks
by Douglas P. Landsittel, Lytt I. Gardner, and Vincent C. Arena 1337

Relative Risk of Involuntary Injuries Among Currently Employed Adults in the U.S.
by Jai Won Choi, Ki Moon Bang, and Robert A. Wright 1353

Table of Contents continued

II. Special Worker Populations

Work-related Fatal Injury Risk of Construction Workers by Occupation and Cause of Death
by G-X. Chen and D. Fosbroke 1371

Robbery-Related Injury in Convenience Stores: Estimating Lifetime Risk and Identifying High Risk Populations
by Kimberly Faulkner, Douglas P. Landsittel, and Scott A. Hendricks 1391

Evaluation of Occupational Injuries Among Young Workers in West Virginia
by P. Simoyi, S. Islam, A. Haque, J. Meyer, E. Doyle, and A. Ducatman 1405

Occupational Noise Sources and Exposures in Construction Industries
by Dale Hattis 1417

Human and Ecological Risk Assessment: Vol. 4, No. 6, pp. 1255-1257 (1998)

PERSPECTIVE

Occupational Injury Risk Assessment: Perspective and Introduction

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Since Congress passed the Occupational Safety and Health Act of 1970, occupational injuries have been increasingly recognized as a major source of life long disability and serious economic loss to workers and employers. The Act established the National Institute for Occupational Safety and Health (NIOSH), and charged it with the enormous responsibility of conducting research and prevention efforts to assure every working man and woman safe and healthful working conditions. Since the 1970s, the numbers and rates of work place injuries and deaths have decreased substantially (Stout, Jenkins, and Pizatella, 1996; CDC, 1998). Moreover, the recognition of both the tremendous toll and the high prevention potential of occupational injuries has increased. However, we are far from eliminating the hazards and risks of injury from our work places, or from dispelling the perception among many that such risks are acceptable as "part of the job." The economic costs to our society of occupational injuries and illnesses rival those of even cancer and heart disease, yet the scientific investment in causes, treatment, and prevention is comparatively trivial (Leigh *et al.*, 1997). Prevention of occupational injuries is not only possible, but is essential to improving the quality of life for millions of American workers. It is also an enormous task and requires a coordinated effort of public and private resources to adequately address the problem. To this end, NIOSH unveiled the National Occupational Research Agenda (NORA) in April 1996. With numerous partners, including those in academia, industry

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and labor, NIOSH developed NORA to provide a framework to guide occupational safety and health research through the next decade for the entire occupational safety and health community (NIOSH, 1996; Rosenstock, Olenec, and Wagner, 1998). The fiscal restraints on occupational safety and health research accentuate the need for a coordinated and focused research agenda, and for harmonization of public and private research efforts and resources.

Out of a tremendous effort, involving sometimes heated debate and discussion about scientific uncertainty, there evolved a remarkable consensus about the top 21 research priorities. The identification and definition of the priority areas of NORA were developed from the broad input of over 500 organizations and individual comments. The NORA effort to guide and coordinate national research was developed to address the most important needs in occupational safety and health and to target efforts to reduce the devastating and unnecessary loss of life and life quality among our workforce.

So that the implementation of NORA would evolve to identify and facilitate more specific and focused research, separate teams of occupational safety and health professionals from industry, labor, academia, federal and state agencies were formed to address each of the 21 research priorities. The *Risk Assessment Methodology Team* and the *Traumatic Occupational Injury Research Team* are two of the results of the NORA implementation process. In an ongoing effort to develop the research agenda in these two specific areas, both teams have independently identified the need for better methodology in the identification of groups of workers at greatest risk for traumatic injury. The *Traumatic Occupational Injury Research Team* recently published a document describing the research needs and priorities for advancing the knowledge and prevention of traumatic occupational injuries (NIOSH, 1998). The document presents a broad research framework for interdisciplinary research and provides a basis for identifying issues and priorities for collaborative research efforts. The Team's purpose was to provide a reference and structure for traumatic occupational injury research which could be used to initiate and facilitate partnerships and collaborative research to further prevention of worker injuries and deaths.

In October 1997, NIOSH, the *Traumatic Occupational Injury Research Team*, and eleven other partnering organizations jointly sponsored The National Occupational Injury Research Symposium (NOIRS) in Morgantown, West Virginia. The NOIRS was the first public forum for the discussion of the feasibility of adapting traditional risk assessment methods for a better understanding of traumatic occupational injury. Of the nearly 200 research presentations given at the NOIRS, one invited session was titled: *Occupational Injury Risk Assessment* and provided the impetus for development of this special topic issue of the *Human and Ecological Risk Assessment Journal*. Interested readers may find more information through the world wide web about NORA (http://www.cdc.gov/niosh/norahmpg.html) and NOIRS (http://www.hgo.net/~noirs/noirs.html), which includes abstracts of the oral and poster presentations.

This issue of the *Human and Ecological Risk Assessment Journal* represents continuing efforts to harness the traditional methods of risk assessment to address the unique problems of occupational injury. Contributors to this special issue address a wide range of topics and interpret the notion of risk assessment for occupational traumatic injury from a variety of different viewpoints. The broad collection of scientific studies provide a foundation for future research that holds promise to significantly enhance understanding of the multifactorial nature of both fatal and nonfatal occupational traumatic injury. The contributions to this special issue include papers that explore innovative methods for use in injury risk assessment and papers that address risk assessment for specific topics or specific populations. The products exhibited here represent exceptional efforts on the part of the contributors to meet the challenge put forth by the NORA *Risk Assessment Methodology* and *Traumatic Occupational Injury Research Teams*.

The dedication of an entire issue of the *Human and Ecological Risk Assessment Journal* to the topic of risk assessment for occupational injury underscores the increasing significance of this field of research and provides a foundation for advancing the development and application of risk assessment methodology for the prevention of occupational injuries.

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Human and Ecological Risk Assessment: Vol. 4, No. 6, pp. 1259-1264 (1998)

DEBATE/COMMENTARY

Injury Risk Assessment for Occupational Safety Standards*

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Key Words: injury risk assessment, OSHA, occupational safety, safety standards

INTRODUCTION

The Occupational Safety and Health Administration (OSHA) is charged with assuring safe and healthful working conditions for working men and women. One tool the Agency has at its disposal is the promulgation of occupational safety and health standards. Before it can promulgate a standard, however, OSHA must first determine that the occupational hazards addressed by that standard constitute a significant risk and that the standard will substantially reduce that risk.

Injury risk assessment, the estimation of the risk of injury or death from injury, is one tool which allows OSHA to make this determination. Traditionally, OSHA has based its significant risk determination for safety standards on estimates of the annual numbers of injuries and/or fatalities associated with exposure to an occupational injury hazard and the number of injuries and fatalities likely to be prevented with a new standard in place. More sophisti-

* **The views expressed represent those of the authors and not necessarily those of the Occupational Safety and Health Administration or the Office of the Solicitor of the Department of Labor.**

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cated data, however, would assist the Agency in identifying risks, making significant risk determinations, measuring risk reduction and the effectiveness of controls, and analyzing the economic and technological feasibility of its proposed safety standards.

BACKGROUND

The Occupational Safety and Health (OSH) Act of 1970 gave OSHA the authority to promulgate occupational safety and health standards. In Section 3(8) of the Act, Congress defined an occupational safety and health standard to mean "a standard which requires conditions, or the adoption or use of one or more practices, means, methods, operations, or processes, reasonably necessary or appropriate to provide safe or healthful employment and places of employment" (29 U.S.C. §§ 651 *et seq.*) It was the Supreme Court's interpretation of these words, "*reasonably necessary or appropriate*," which initiated OSHA's foray into quantitative risk assessment.

In 1978, OSHA promulgated a new standard for occupational exposure to benzene. Based on the belief that no safe exposure level could be determined for a carcinogen, OSHA reduced the permissible exposure level (PEL) from 10 ppm to 1 ppm on the grounds that a PEL of 1 ppm was the lowest technologically feasible level that would not impair the viability of the industries affected by the standard. The benzene standard was challenged in court on the grounds that OSHA had exceeded its standards-setting authority by not showing that the new PEL was reasonably necessary or appropriate to provide safe or healthful working conditions.

In its ruling the Supreme Court wrote that "before he can promulgate any permanent health or safety standard, the Secretary is required to make a threshold finding that a place of employment is unsafe - in the sense that significant risks are present and can be eliminated or lessened by a change in practices . . . As we read the statute, the burden was on the Agency to show, on the basis of substantial evidence, that it is at least more likely than not that long-term exposure to 10 ppm of benzene presents a significant risk of material health impairment." Noting that "the requirement that a 'significant' risk be identified is not a mathematical straightjacket," the Court wrote that OSHA "is not required to support its finding that a significant risk exists with anything approaching scientific certainty." Rather, "so long as they are supported by a body of reputable scientific thought, the Agency is free to use conservative assumptions in interpreting the data with respect to carcinogens, risking error on the side of overprotection rather than underprotection" [*Industrial Union Department, AFL-CIO* v. *American Petroleum Institute*, 448 U.S. 607 (1980)].

Since the Supreme Court handed down its "Benzene" decision, OSHA has issued a number of health standards for which it has quantified risks at existing exposures, concluded risks were significant, estimated risks under new exposure limits, and measured the reduction in risk likely to be achieved by the new standards. Health standards which have been promulgated using this approach have been upheld in court.

In 1989, OSHA promulgated a standard regulating the control of hazardous energy sources (Lockout/Tagged). It was clear that the new standard would reduce a substantial number of both injuries and fatalities. Industry challenged the standard, however, on the grounds that the OSH Act provided so little guidance on the setting of standards that it invalidly delegated legislative authority to the Agency. OSHA disagreed. Its position was that under Section 3(8) of the Act, once the Agency made a threshold finding of significant risk to workers and determined that the proposed controls were technologically and economically feasible, it had broad authority in devising a regulatory response so long as the requirements were feasible. Both positions were rejected. The Court of Appeals for the District of Columbia Circuit remanded the standard to the Agency for the reconsideration of the scope of the Agency's discretion to adopt standards that are "reasonably necessary or appropriate" [*International Union, United Automobile Workers* v. *Occupational Safety and Health Administration*, 37 F.3d 665 (D.C. Circuit, 1994)].

In response to the Court, OSHA developed a policy clarifying the Agency's discretion in choosing a safety standard. Among the constraints to its discretion, which were accepted by the Court and represent current OSHA policy, are the requirements that a safety standard must substantially reduce a significant risk of material harm, that there must be evidence in the rulemaking record to support the Agency's choice of standard, that a standard must be technologically and economically feasible, and the standard must provide "a high degree of employee protection" ["Control of Hazardous Energy Sources (Lockout/Tagged); Supplemental Statement of Reasons," 58 *Federal Register* 16612, March 30, 1993.].

OSHA INJURY RISK ASSESSMENT

OSHA has acknowledged that risk assessments should be put in quantitative terms to the extent possible. OSHA injury risk assessments, however, are usually quite different than OSHA health risk assessments. While both are used to determine the significance of risk of material impairment, health risk assessments are usually based on toxicological studies of laboratory animals and/or historical prospective and retrospective epidemiological studies when such studies are available. The health standards for which these risk assessments are done usually address hazards which result in serious illness (*e.g.*, lead poisoning, byssinosis, etc.) or death from illnesses long after the onset of exposure. Such outcomes clearly represent material impairment of health.

In contrast, injury risk assessments are usually based on large surveys such as the Annual Survey of Occupational Injuries and Illnesses conducted by the Bureau of Labor Statistics (BLS). Often, the exact outcome of exposure to these safety hazards is not specified. OSHA does not quantify the number of fractures, the number of sprains, the number of lacerations, etc., which may result from exposure. Instead, different types of injuries are typically aggregated, and their severity is most often measured in terms of lost workdays.

The safety standards for which these injury risk assessments are done usually address hazards which result in instantaneous outcomes such as becoming caught in moving machinery parts or falling from unguarded scaffolds. These standards aim to reduce the risk of death as well as the risk of many other less severe outcomes. For example, OSHA's Lockout/Tagged standard aims to prevent fatalities due to workers being caught in running machinery as well as amputations, broken bones, and bruises. OSHA's hand protection standard aims to reduce risks from skin absorption, severe cuts or lacerations, severe abrasions, punctures, chemical and thermal burns, and risks from harmful temperature extremes.

The Supreme Court provided guidance to the Agency in making its significant-risk determination when the outcome of interest is death. In its "Benzene" decision [*Industrial Union Department, AFL-CIO* v. *American Petroleum Institute*, 448 U.S. 607 (1980)], the Court wrote:

> "If, for example, the odds are one in a billion that a person will die from cancer by taking a drink of chlorinated water, the risk clearly could not be considered significant. On the other hand, if the odds are one in a thousand that regular inhalation of gasoline vapors that are 2% benzene will be fatal, a reasonable person might well consider the risk significant and take appropriate steps to decrease or eliminate it."

The Supreme Court has provided no similar guidance when the outcome of interest is something other than death. Instead, OSHA has made this determination on a case-by-case basis.

OSHA'S DATA NEEDS FOR INJURY RISK ASSESSMENT

Injury risk assessments should incorporate all relevant lines of scientific evidence. Evidence from epidemiological studies of occupational injuries is helpful not only for quantifying risk but also for measuring the reduction in risk achieved after applying control technologies. While engineering, mechanics and material science allow identification of some occupational injury hazards and alternative solutions, often epidemiological methods are better for hazard assessments in human populations, for surveillance of the effects of alternative control strategies on exposure patterns, and for measures of population risk and injury occurrence. Thus, injury epidemiology data would improve OSHA's injury risk assessments.

There are at least four types of research which would be helpful to OSHA in performing injury risk assessments in support of its safety standards activities. First and foremost are studies which identify occupational hazards resulting in material impairment. Not only must the hazard be identified, but the risk factors which contribute to the hazard must also be identified. Large surveys like the BLS Annual Survey of Occupational Injuries and Illnesses and the Census of Fatal Occupational Injuries have limited utility for injury hazard identification. They tend to focus on the nature of injury (*e.g.*, dislocations, fractures, etc.), type of injury (*e.g.*, falls to lower level, falls on same level, etc.), and source of injury (*e.g.*, ladders, stairs, etc.), individually rather than in combination. Data which associate source of injury with type and nature of injury and identify competing risk factors are better for identifying emerging hazards.

Second are studies of the magnitude of the risk associated with occupational exposure to an injury hazard to determine whether the risk is significant. Studies should be designed such that competing risk factors are controlled so it is clear that the observed outcome results from exposure to a specific hazard or group of hazards. These data may be either site or industry specific so long as there is nothing to preclude extrapolating risks to other sites or industries.

Third are studies which quantify reduction in risk from exposure using a variety of control methods. For example, if OSHA had injury risk data from one site which uses a particular piece of equipment with no controls and data from another site which uses the same piece of equipment but which had instituted controls, then OSHA would be able to quantify the reduction in risk achieved by instituting controls. If OSHA had data from multiple sites using the same piece of equipment but each site had instituted different control methods, OSHA would be able to identify the control method which led to the greatest reduction in risk, and among methods which lead to equal reductions in risk, OSHA would be able to identify the control method which was most cost effective.

Last are studies to estimate the number of workers exposed to a hazard and the number and type of worksites where the hazard is found. These data allow OSHA to characterize the risk of exposure to an occupational injury hazard. They are also useful in helping OSHA determine economic feasibility, and they help OSHA quantify the benefits from a new standard.

It is preferable, where possible, for observational studies to be conducted with rigor. Exposures should be clearly characterized and outcomes should be clearly defined. Estimates of the population at risk are also important. It is preferable for data to come from multiple sources. This allows OSHA to draw its inferences with greater confidence. In addition, the limitations of any research should be explicitly stated, thereby allowing OSHA to accurately represent its assumptions when making estimates using these data.

It is not hard to imagine examples of research which would support OSHA's safety rulemaking activities. One project underway is the development of a final rule to reduce injuries from slips, trips, and falls. Research which addresses issues such as the circumstances under which slips, trips and falls occur; the effectiveness of various controls and procedures in reducing these occurrences; the effectiveness of diamond plate versus rubberized surfaces or slip-resistant paint in preventing slips and falls; and the effectiveness of various types of guard rails are all examples of the kind of research which would support the Agency in its efforts.

Similarly, catastrophic explosions are a continuous problem in certain industries. OSHA's Process Safety Management standard, which was designed to address these hazards, is a performance-oriented standard. Studies on the effectiveness of various approaches allowable under the standard, measured by reduction in the number of explosions and/or by reductions in the number of fatalities from an explosion, would be of great use to the Agency.

In addition to research needs, OSHA needs input from the scientific community to assist the Agency in improving its injury risk assessment policy. OSHA turns to this community to address the following questions:

1. What constitutes material impairment when an adverse outcome is less severe than death? Should certain outcomes be considered material impairment of health or should the determination be made on some other basis such as median days away from work?

2. What constitutes significant risk when the outcome of interest is less severe than death? On what measure should the significant risk determination be based? Typically, OSHA has looked at number of injuries resulting from exposure to a hazard and, when such data are available, the lost-workday incidence rate resulting from the exposure. Other possible measures include the total injury rate and the days away from work rate.

3. How should risks be expressed? Rates derived from the BLS survey are annual rates, but these rates provide no measure of the magnitude of the risk a worker faces cver an entire working lifetime. At present, however, there are no statistical models to estimate lifetime risk when the outcome can occur multiple times over a working lifetime. Furthermore, it is by no means clear that each injury a worker may sustain is an independent event. This violation of the assumptions of the binomial distribution must be accounted for in any injury risk assessment model.

OSHA turns to the scientific community for help in answering these questions either on a hazard-specific or a general basis. OSHA also looks to the scientific community to provide the research needed for the Agency to fulfill its mission of assuring safe and healthful working conditions for working men and women.

Human and Ecological Risk Assessment: Vol. 4, No. 6, pp. 1265-1274 (1998)

Comparing Injury and Illness Risk Assessments for Occupational Hazards

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ABSTRACT

One common framework for describing the evaluation and assessment of hazards in the workplace includes the four steps of hazard identification, exposure assessment, exposure-response modeling, and risk characterization (NAS, 1983). We discuss hazards for occupational injury and illness in light of this framework, and we contrast the evaluation of injury hazards with the evaluation of illness hazards. In particular, the nature of the hazards, typical exposure patterns, quantification of exposure, and the attribution of outcome to exposure are discussed. Finally, we discuss the management of occupational illness and injury hazards and issues encountered when evaluating efforts designed to mitigate the effects of occupational hazards.

Key Words: hazard identification, exposure assessment, exposure-response modeling, risk characterization, risk management, intervention research

INTRODUCTION

Risk assessment for acute traumatic injury, in contrast with occupational disease, appears to have received less attention in the research and regulatory arenas. We compare and contrast the assessment and evaluation of occupational injuries and diseases in the context of a widely used risk assessment model (National Academy of Sciences, 1983). The assessment and evaluation of the effects of occupational illness and injury are both challenging activities.

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The risk assessment process requires that a series of questions be answered. How should such "effects" be defined? Can we easily link exposure to some hazard in the workplace to a particular adverse response? What sources of human and experimental data are available that might give insight into this problem? If we can identify relevant data sources, are they of sufficient quality for use in the quantification of the "risk" associated with exposure to occupational hazards? If positive answers can be found for each of the questions above, can we determine exposure limits to hazards that are both protective to the health of the worker and yet are technologically and economically feasible? These questions span the gamut of concerns encountered in the risk assessment and management of occupational hazards.

For the discussion that follows, "risk" is used to refer to the likelihood of some adverse response associated with an occupational hazard that has the potential for causing harm to the worker. Examples of occupational illnesses and their associated hazards include chronic obstructive pulmonary disease associated with coal dust exposure and leukemias or other cancers associated with benzene exposure. Examples of occupational injuries include a fatal injury associated with being crushed in a machine during maintenance as a result of the failure to use a lockout/tagout system or breaking a limb as a result of a fall from a scaffold. As we discuss in later sections, the nature of both the hazard and the response may differ when considering the risk assessment of injuries and illnesses.

The model we use to discuss the risk assessment of occupational hazards was first summarized by the National Academy of Sciences (1983). In this model, risk assessment is considered a four step process comprised of the following components: (1) hazard identification; (2) exposure assessment; (3) dose-response modeling; and (4) risk characterization. A summary of how occupational illnesses and injuries differ with respect to these four components is presented in Table 1. An integration of the pieces of a risk assessment with the economic costs and considerations associated with risk regulation and control technologies is often labeled "risk management". Finally, an evaluation of the effectiveness of risk regulations and other control measures, so-called "intervention research", is also of concern. A summary of how occupational illnesses and injuries differ with respect to risk management and intervention research is presented in Table 2. While our focus is on the four risk assessment pieces, we will describe some differences between risk management and intervention research for occupational illness and injury.

HAZARD IDENTIFICATION

How do we know that some agent might be a hazard? Hazard identification describes the step in the risk assessment process during which an exposure is identified as having the potential to lead to some adverse health response. With hazards that might be associated with occupational cancers, we might have information on the mutagenicity of the hazards based upon genetic toxicology tests or we might have the results of long-term animal carcino-

Table 1. A comparison of occupational illness and injury with respect to the components of a risk assessment.

Risk Assessment component[a]	Occupational Illness	Occupational Injury
Hazard Identification		
Does exposure to an agent increase the incidence of a health condition? Nature/evidence of causation? Carcinogenicity tests? Short-term tests? Structural activity relationships?	Difficult Causation may be difficult due to the latency between exposure and disease Disease mechanistic data may be critical Same exposure may have multiple outcomes and single outcomes may have multiple causes	Immediate effect of exposures generally makes hazard identification easier for injuries Causation between exposure and injury easily established Mechanistic data not critical
Exposure Assessment		
Intensity, frequency, duration of human exposures? Hypothetical exposures for new chemicals Magnitude, duration, route of exposure Size, nature and classes of human populations exposed Uncertainties Extent of exposure before or after regulatory controls	Estimates of historic exposure difficult to obtain May appeal to industrial hygiene job-exposure matrices or other tools	While intensity of exposure may not be critical, duration and frequency of use may be key feature Information on exposure of the victim and other members of the cohort difficult to ascertain Job safety analysis or job hazard analysis can be done for each discrete job or task
Exposure Response Modeling		
Characterizing the relation between agent dose and adverse response incidence Incorporates intensity of exposure, other variables (confounders, effect modifiers) Extrapolation issues (dose, species) Uncertainties (statistical, biological)	Exposure generally continuous Disease mechanism may be considered to suggest a particular statistical model	Exposure generally discrete Mechanistic data generally not considered Statistical modeling, if done, is mostly empirical
Risk Characterization		
Nature/magnitude of human risk	Lifetime estimates of risk generally presented	Most often expressed as rates or years of potential life lost Working lifetime risk occasionally considered

[a] Follows framework/definitions suggested by NAS (1983) report.

Table 2. Differences in risk management and intervention research between occupational illnesses and injuries.

	Occupational Illness	Occupational Injury
Risk Management		
Compare regulatory options (consider public health, economic, social, political concerns)	Exposure-response required by some agencies	Exposure-response information usually not considered/ required
Intervention Research		
Examine the efficacy of the regulatory intervention suggested in the risk management component of the risk assessment process	May only monitor reduction in exposure with hopes that incidence of adverse response will also be reduced because of long latency	Incidence rates can be directly monitored (at least in theory)

genicity experiments suggesting that a particular compound induced cancer in a mammalian model, or we might recognize that a particular agent shares structural similarities with a known hazard. For occupational diseases, knowledge of the disease process might be critical in the identification of disease. For example, if decreased lung function is associated with the clearance mechanism of the lung being overwhelmed, then a hazard (*e.g.*, silica dust) might be identified as an agent that would inhibit lung clearance. The hazards for occupational illness are often chemicals and particulates, although radiation and noise are also recognized as hazards. There are two particular challenges in recognizing illnesses associated with particular exposures. One special challenge associated with identifying hazards associated with occupational illness is that the disease process initiated by exposure to the hazards may not be manifest for many years following exposure. The long latency between exposure and illness makes the attribution of disease to hazard exposure very difficult. The other challenge comes from the diseases resulting from occupational exposure often having non-occupational etiologies as well. Thus, vinyl chloride was easily recognized as a cause of angiosarcoma of the liver since this disease only rarely occurs otherwise. In contrast, it is more difficult to discern that bladder cancer has resulted from a specific occupational exposure as its non-occupational incidence is substantial.

In contrast, the identification of hazards associated with occupational injury appears obvious at one level. Injuries result from the transfer of energy and have been characterized using concepts from infectious disease epidemiology

(Robertson, 1992). Thus, any situation in which it is reasonably anticipated that energy in any form (*e.g.*, mechanical, electrical, heat) can be transferred to a person or from a person (*e.g.*, falling to a stationary surface) at a sufficiently high intensity to cause injury would be identified as hazardous. While a chemical might easily be identified as a possible hazard of occupational illness, industrial processes or situations are more commonly identified as hazards for occupational injuries. For example, when multiple serious injuries were observed as a result of tractor rollovers, the high center of gravity and the lack of a roll bar on tractors along with the use of tractors on inclines were identified as hazards (NIOSH, 1993). However, while the direct cause of an injury is often obvious, the difficulty in establishing the sequence of events that lead to the injury should not be underestimated. For example, while it may be obvious that a victim fell from a ladder, there is often inadequate information to reconstruct if the ladder feet slipped out, or the ladder slipped sideways, or the victim slipped from the rung.

EXPOSURE ASSESSMENT AND EXPOSURE-RESPONSE MODELING

Once a hazard has been identified, we want to know the size of the exposed population and level of exposure. In addition, we want to know the pattern, amount and route of exposure. These are the questions that make up the exposure assessment phase of a risk assessment.

In general, it is easier to determine if someone is exposed at work than it is to determine the magnitude of their exposure. Often the manufacturing process will immediately suggest the types of hazards present. For example, 1,3-butadiene is associated with manufacture of synthetic rubber while methylene chloride is encountered in the photographic film manufacturing industry. Taking the next step to determine who is exposed and to how much of the chemical is more difficult.

The nature of exposure patterns suggests a possible difference between occupational diseases and injuries. The usual pattern of exposure for hazards associated with occupational diseases is often a long-term, chronic pattern. As noted above, defining this cumulative level of exposure in the workplace may be difficult. Job classifications using the input of industrial hygienists is typically used to identify exposure levels associated with various job titles while individual worker exposure levels are often inferred from job histories in conjunction with the previous industrial hygiene assessments. Environmental monitoring and biologic monitoring can, however, provide a benchmark from which to estimate prior exposures. For occupational illness, this is an important exercise since the cumulative exposure to occupational hazards is often employed in later exposure-response assessments of chronic illness and disease. This calculation is based on the assumption that a worker exposed to an agent suspected of causing an occupational illness may spend their entire shift exposed to the agent at a constant level of exposure associated with their job title. For occupational disease, there is usually some historical record that gives an approximation of the level of exposure of members of the cohort, whether diseased or not. While cumulative exposure has been commonly employed as a exposure metric in occupational illness risk assessment, many of the models of cancer allow for the possibility that a single exposure to a cancer-causing agent may be sufficient to initiate the disease process which may not be observed for many years. Thus, an acute exposure event may induce an occupational illness.

Occupational injuries usually result in response to an acute exposure event. To illustrate, suppose a worker is injured from the failure of a lockout/tagout system that was intended to protect workers during the maintenance of a machine. The worker may spend a small fraction of their shift at risk for the failure of the lockout/tagout system. While injuries may result in response to an acute exposure event, the precursor to this event may occur frequently without incident. For example, a worker may use a ladder many times without injury occurring prior to having an injury resulting from a fall from the ladder. Thus, the number of times a ladder was used might provide a cumulative measure of exposure to the injury hazard. Furthermore, there are some musculoskeletal injuries, such as carpal tunnel syndrome, which are the result of repetitive trauma and thus truly are best represented by cumulative exposure.

The concept of a "working lifetime" may be an important quantification of exposure and its use in risk assessment (Fosbroke *et al*, 1987). The period of time over the course of a worker's employment history when a worker is employed in a given craft or job category (*e.g.*, loggers, forklift operators) may provide a cumulative measure of exposure for the hazard of injury. One potential difficulty with this type of exposure measurement is that workers are assumed to be at the same risk of injury at all ages and that the workplace risk of injury remains constant for a long period of time. Both of these assumptions are questionable. Older workers generally experience higher rates of injury (See and Bailer, 1998) and the workplace has tended to become safer over time (Bailer *et al.*, 1998).

Dose-response or exposure-response modeling are general phrases for describing the component of the risk assessment process in which hazard exposure levels are related to the adverse response of interest. This requires some confidence that the response can be attributed to exposure. This may be quite difficult for occupational illnesses and diseases. As noted previously, occupational illnesses often occur long after exposure to the suspected hazard. This long latency between exposure and disease makes the study of exposure-disease relationships very difficult. In contrast, exposure to energy, the occupational hazard for injury, and the adverse response often are directly and clearly related.

Assessment of exposure to injury hazards has not typically been determined. Often measurements of the hazard are neither available for the injured worker, for example how high was the victim on the ladder, nor is similar information available to characterize other members of the cohort who have not been injured. Once an injury occurs in the workplace, a "job safety analysis" or "job hazard analysis" may be conducted. In this analysis, the jobs are broken down into tasks where the hazards and control measures employed are documented. If these analyses are conducted within a particular company, these data are generally not available on a national basis, and hence are not available for occupational injury risk assessments conducted on a very broad scale. The investigation of occupational injuries by OSHA and others have attempted to document the sequence of events preceding the injury using a case study approach. This approach is not amenable to estimating risks or modeling exposure-response relationships.

Selecting a mathematical form that underlies many risk assessments for occupational hazards is somewhat arbitrary since many empirical models may fit the available data equally well. Unfortunately, the choice of statistical models may result in dramatically different estimates of risk for low exposure scenarios. For illness, a variety of statistical tools are employed to study how illness is related to the effects of the hazard, a risk factor of interest, along with other variables, potential confounders or effect modifiers. Logistic regression, Cox regression models and a host of other relative risk regression models are used for this exercise. Examples of how risk estimates differ with regression models can be found in Stayner *et al.* (1997). In addition, models reflecting mechanisms of disease might be considered when describing exposure-illness response patterns (for example, the multistage and mutation-clonal expansion models for carcinogenesis). In contrast, the use of exposure-response models for injury outcomes are fairly rare. Typically, stratified analyses of injury outcomes by levels of certain classification variables are conducted. For example, injury rates might be represented separately for different industries or for different worker ages. Models that are employed for analyzing occupational injury data include Poisson regression (Bailer *et al.*, 1997) while recent research efforts are focused on defining and estimating lifetime risk for occupational fatal injury (Fosbroke *et al.*, 1997; See and Bailer, 1998). We believe that there is a strong need to continue research to determine the most valid models for evaluating injury events and to critically evaluate the validity and utility of current approaches. In conclusion, the definition/quantification of exposure may be more difficult in injury hazards relative to illness hazards while the attribution of disease to hazard exposure may be more difficult for illness hazards relative to injury hazards.

RISK CHARACTERIZATION

The last stage in the risk assessment process according to the National Academy of Science model is the risk characterization step. At one level, this step focuses on integrating the previous steps of the risk assessment. The results of the exposure-response model are integrated with the assessment of worker exposure with a goal of evaluating the degree and extent to which an occupational hazard poses a risk to human health. In particular, lifetime risk projections for occupational illness are often produced to address this goal. While this is common in illness risk assessment, it is rarely, if ever, considered in injury risk assessment. One difference between illness and injury risk assessments is that the populations at risk of adverse response might be quite different. For many occupational hazards associated with illness, the population at risk may be employed in a very specific industry. In contrast, with many hazards associated with occupational injury, the populations at risk may span many different industries. To illustrate, any industry in which electricity is employed may have workers at risk of electrocution while 1,3-butadiene might be used in a very small group of industries manufacturing a particular product. Finally, because of the requisite interval from exposure to onset, illness is more likely to occur in older workers in contrast to injuries. The median age of death in a large database of occupational fatal injuries was 35 years (Gilbert *et al.*, 1998). The effects of occupational illness may not be manifest until a much later age. Thus, the years of potential life lost due to occupational fatal injuries might be larger compared to the years of potential life lost due to occupational illness.

Prediction of risk outside the range of human observation is problematic for occupational disease and injury. For disease, the controversy primarily centers on two issues. One is the shape of the dose response curve at low levels of exposure and whether there is a threshold below which adverse effects are not observed. The other difficulty is predicting illness in humans from data that is derived from experimental animals. There are similar difficulties in predicting human injury from studies of mannequins, and in predicting injury across age, size, and other body characteristics.

RISK MANAGEMENT AND INTERVENTION RESEARCH

After a risk assessment is completed, a decision must be made as to what intervention is warranted. The level of intervention may range from alerts to notify workers of the possible danger associated with certain hazards to a regulatory intervention in which a standard is promulgated mandating a reduction in exposure to a hazard (*e.g.*, OSHA standards for 1,3-butadiene or methylene chloride) or mandating a control technology (*e.g.*, respirators or lockout/tagout devices).

The 1980 Supreme Court decision on benzene firmed up the need for OSHA to do risk assessments for both health and safety standards rulemaking (Reed *et al.*, 1994; Martonik *et al.*, 1998). In this ruling, an initial mark of 1 in 1000 additional cancers was suggested as significant risk associated with exposure to a hazard while a 1 in 1,000,000,000 additional cancers was not. Obviously, much room exists between these two levels, and this has been a topic of continued debate in the setting of regulatory standards. While lifetime risk has been employed to set occupational health standards, it has not been used for safety standards. Recent work (Fosbroke *et al.*, 1997; See and Bailer, 1998) describing lifetime risk for injuries among different occupations is promising for allowing similar arguments to be employed for setting safety standards.

Intervention research could assess the effectiveness of an intervention such as a regulatory standard or a change in design, such as air bags in automobiles, after it has been promulgated or implemented. This research evaluates that effectiveness of a standard. Did the regulatory standard induce changes that improved worker health and safety? If this activity is initiated shortly after the passage of a standard, insufficient time may have passed to observe the desired outcome. This is especially true for standards that were passed to control hazards associated with occupational illnesses and diseases that occur with a fairly long latency after exposure. In this situation, it may only be possible to assess if the workplace exposures have been reduced to levels that are considered to possess minimal risk based upon projections from exposure-response modeling. We may also need to wait until the standard is fully implemented prior to seeing if improvement in health or safety is observed. For intervention research associated with occupational injuries, an effective rule might be expected to have immediate impact on the occurrence of occupational injuries. One difficulty in assessing such a change is that industries may begin modifying the workplace while the standard requiring such modifications is being debated. Given that it takes years to bring a standard from suggestion to law, changes associated with the rule could be difficult to determine. To address this concern, the monitoring of worker injury and illness must be an ongoing activity. To see changes designed to influence to safety in the workplace, we need a long record of observation that extends from before a standard is even proposed to 3-5 years or more after a standard is in effect.

SUMMARY

Our objective was to provide an introduction to the process of risk assessment for occupational hazards with an exploration of the similarities and the differences that exist between evaluating illness and injury. We see that illness and injury might pose different challenges both during and after a risk assessment. Both illness and injury risk assessments would benefit from greater assessment of the magnitude and frequency of occupational exposures to hazards. This type of data would be available if broad and ongoing industrial hygiene evaluations were conducted. These data would provide a better basis for exposure assessment and exposure-response modeling. A special problem that may arise in exposure-response modeling arises with non-fatal injuries in which particular workers may experience the adverse response on more than one occasion. Techniques for analyzing recurrent events may need to be employed to address these problems. Risk characterization needs include continued investigation in the appropriate means of evaluating the lifetime risk of illness and injury hazards. Recent work has extended these concepts for injury outcomes; however, adjustments for age-specific injury rates and time trends in injury rates are only now being explored. Finally, if we want to assess the effectiveness of regulatory interventions, we need to have better monitoring of illness and injuries in industries both before and after regulatory interventions.

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Probability Models of Occupational Injury

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INTRODUCTION

Probability models are an attempt to describe the random mechanism underlying events for which the outcome is uncertain. In injury risk assessment, these models provide the basis for developing and evaluating summary measures of the incidence of occupational injuries for comparison of occupations and industries. Probability models are used to represent the mechanism by which injuries occur to some individuals, while other individuals are not injured, under similar circumstances. Methods for statistical analysis of occupational injury data require assumptions based on a reasonable mechanism describing the random nature of the occurrence of events, after accounting for all observable injury determinants.

Probability models are an important consideration whether the data are obtained as a sample of a larger population, or if the data describe all the events in a well-defined population (*i.e.*, a census). In either case, events, such as occupational injuries, require a probability model in the absence of complete information to perfectly predict injury events. After accounting for individual characteristics and explanatory factors that may affect injury risk, the fact remains that some individuals are injured and some, under similar circumstances, are not injured. Thus a probability model is needed to describe the nondeterministic nature of injury incidence.

Probability models must be distinguished from statistical models which are usually formulated with the primary consideration of residual error or sampling variability (Choi and Bang, 1998). In the application of regression or

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linear models, emphasis is often placed on the necessary assumption that residual error terms have a gaussian (normal) distribution with zero mean and constant variance. Researchers are frequently willing to accept this assumption, almost without validation, because it permits inference and testing of the parameter estimates. Assessing the validity of the underlying random process for a specific application requires going beyond the routinely recognized textbook language of model assumptions. It is important to recognize the limitations of probability models that we find useful, through a complete exploration of the underlying random mechanism they attempt to describe.

Identifying, with certainty, those occupations and industries that are at high injury risk can be a difficult analytical problem that may be resolved through the consideration of probability models. Explicit definition of the random variables and their associated probability distributions permits a greater understanding of the strengths and limitations of comparisons based on the summary measures. The *working lifetime risk*, which is the probability that a work related fatal injury occurs during a 45-year working lifetime, has been proposed as a measure that allows comparison of occupational illness and occupational injury (Fosbroke, Kisner, and Myers, 1997; Bailer *et al.*, 1998). A threshold value of one fatality in 1000 workers in a working lifetime has been used for setting occupational health standards and provides motivation for the use of this metric in setting occupational safety standards (Martonic, Grossman, and Gordon, 1998). The working lifetime risk can be shown to be the result of several different probability models, which describe different types of random variables, based on different mechanisms for the random occurrence of injury.

This paper explores the applications of some elementary probability distributions for occupational injury data; examines the concept of working lifetime risk using several different probability models; considers the working lifetime risk and alternative metrics for comparison of occupation and industry groups; introduces the limit form of the working lifetime risk; demonstrates that time-until-event methods can be used to estimate the working lifetime risk; and mentions additional unique characteristics of occupational injury data. The limit form of the working lifetime risk demonstrates that the application of survival analysis methods to occupational injury data provides a generalization of the working lifetime risk.

PROBABILITY MEASURES OF OCCUPATIONAL INJURY EVENTS

Binomial Probability Models

The most common way in which probability is defined is as a *relative frequency* measure of the probability of an event. Simply stated, a researcher first identifies a situation involving repetition of identical trials and counts the number of times a particular outcome occurs. A ratio of the count of the number of some specific outcome, to the total number of trials observed, provides an estimate of the probability that the outcome will be observed on future attempts.

To estimate the probability of occupational fatal injury, researchers observe the number of workers experiencing a fatal injury in a particular occupation, over some specific time period (*e.g.*, 1 year), and divide by the number of persons employed in that occupation. For this discussion, this ratio will be denoted as $\hat{p}$. This number describes a situation that has already occurred, based on past data, and provides some estimate of the probability that a worker in a particular occupation will experience a fatal injury in the future, if all other factors that might affect fatal injury incidence remain the same. The number is useful even without the need to consider future events; this number can be used to characterize the past, if the goal is to compare past performance of different industries or occupations.

In occupational injury risk assessment, interest is usually centered on the probability of a fatal injury occurring to an individual worker during some fixed, usually pre-specified time interval. Considering a group of employees in an occupation or industry, more than one fatal injury may occur, to a different individual, of course, without much change in the estimated probability of injury, $\hat{p}$, when the total number of workers is large. The numerator of the relative frequency estimate counts each fatality only once and represents a subset of the total number of workers at risk in the denominator. The discussion of repeated non-fatal, recurrent injuries poses difficult analytical problems related to correlated random variables requiring complex probability models that form the basis of advanced analytical methods which will be discussed later in the context of survival analysis techniques.

Depending on the intended use of the relative frequency estimate $\hat{p}$, it will be interpreted differently. An individual who works in a particular industry or occupation may consider this number as an estimate of the probability of a fatal injury on the job and it might direct individual career goals or financial planning. The number provides an answer for the question: "What is the chance I will be injured in this job during the next year?" Researchers, for example, in the insurance industry, may interpret this relative frequency estimate as the probability that one or more claims will be received during some period of time. The proportion might be used to determine the expected number of fatalities by multiplying $\hat{p}$ times the best estimate of the number of employed that are "at risk" for injury. In this setting, the number is considered to represent a probability for the members of a large group of employees rather than for an individual employee. This is more consistent with the process routinely used to obtain the data in occupational injury studies and extends the interpretation of $\hat{p}$ to characterize a group of workers in a particular occupation or industry.

The number of observed injuries may be represented as a binomial random variable, $X = 0, 1, 2, \ldots, n$, with the following formula representing the probability that X injuries are observed: $P(X = x) = {}_nC_x p^x(1 - p)^{n-x}$ where the notation ${}_nC_x$ is the combination or number of ways of selecting X items out of a group of N. In order to use this probability model, the probability of injury for each individual must be constant, and not be affected by whether or not another worker is injured (independent events). The relative frequency estimate, $\hat{p}$, serves as an estimate for p, in this formula.

Consider a modification of the previous situation, where we observe a group of workers over a long period of time, say 45 years, from age 20 to age 65. The binomial probability model can be used to address the question: "What is the probability that there is *at least one* year in which there is at least one work injury among a large group of employees during the working lifetime of 45 years?" The probability estimate needed should indicate the relative frequency of occupational injury occurring in any one year, *i.e.*, the number of years in which injuries occur divided by the number of years for which data are available. Ideally, the estimate would be obtained by counting the number of fatal injuries that occur in a large group of employees over a 45-year observation period. The estimate, $\hat{p}$, based on injuries per workers, is used as an estimate of the probability of injuries per year, in the absence of the ideal estimate.

Age-group or other group specific probabilities can be used to describe the injury counts stratified by age or other groups, if available, call them $\hat{p}_i$, where i is an index that identifies the age-specific probabilities. Another option is to make the simplifying assumption that the probability of injury is constant for all ages, $p_i = p$ for all values of i.

Note that there are 45 different ways that exactly one injury can occur in 45 years and there will be ${}_{45}C_2 = 990$ ways that two injuries can occur in 45 years, ${}_{45}C_2 = 14{,}190$ ways that three injuries can occur in 45 years, etc. We calculate the sum of all the probabilities associated with the different combinations or, to simplify the problem, consider the *complement* of the event to obtain an answer. $P(X \geq 1) = 1 - P(X = 0)$. Because the probability of zero injuries in a 45-year lifetime is estimated as $(1 - \hat{p})^{45}$ or $\Pi_i(1 - \hat{p}_i)$ for age-specific probabilities, then the probability of *at least one* year in which there is at least one work injury during the working lifetime is $1 - (1 - \hat{p})^{45}$ (Fosbroke *et al.*, 1997) or $1 - \Pi_i(1 - \hat{p}_i)$ (See and Bailer, 1998) which are two representations of the *working lifetime risk* for occupational injury. (Note that, for convenience, the working lifetime risk is usually defined as the value obtained above multiplied by 1000; because the constant multiplier has no effect on the discussion of probability models, it will be ignored in this discussion.)

This model is based on a prospective viewpoint, anticipating all possible outcomes for the entire 45-year period. The working lifetime risk uses no information from historical data about the proportion of years in which injuries have been known to occur, although it is rare to find a well defined occupational group with a reasonable number of employees who were injury-free for an entire year. Note that the use of $\hat{p}_i = \hat{p}$, for all i, results in an estimate of the working lifetime risk that is equivalent to an order invariant transformation of the $\hat{p}$ (working lifetime risk is a nearly linear function of $\hat{p}$ over the range of typical values) when comparing different occupations or industries (Chen and Fosbroke, 1998).

The Geometric Distribution

An alternative formulation is more specific to fatal occupational injury risk assessment from the viewpoint of the probabilities perceived by an individual. Consider the following setup: over a period of 45 years an individual worker may have an estimated probability, $\hat{p}$, of an occupation-related fatal injury each year. The number of years involved in the calculation of the lifetime probability varies from individual to individual and ends on the year of the worker's fatal injury. If the number of years survived, $Y = 0, 1, 2, \ldots$, is counted for each individual, this number is a random variable with the geometric distribution, often referred to as the number of trials preceding an event. Unlike the binomial random variable, the maximum of a geometric random variable is not restricted to the number of trials, although the underlying probabilistic structure is identical, requiring independent trials with a constant probability of a fatal injury. This is a retrospective approach, starting with the year in which the fatal injury might occur and multiplying by the probabilities that no fatal event occurs in the years of life prior to the year of the fatal injury, while the worker is "at risk" of a fatal injury. In the case of working lifetime risk, the $P(Y < 45)$ is the sum of the probability for the events where an individual dies from a fatal injury in year one, added to the probability of the event that an individual dies in year two, etc.

$P(Y = 0) + P(Y = 1) + P(Y = 2) + \cdots + P(Y = 44)$, which is: $\hat{p} + (1 - \hat{p})*\hat{p} + (1 - \hat{p})^2*\hat{p} + \cdots + (1 - \hat{p})$. In general, this is the sum of the geometric series: $P(Y < k) = \Sigma_{y=0}^{k-1} (1 - p)^y p = 1 - (1 - p)^k$. Again, this quantity, which has developed out of a different probability model, is known as the *working lifetime risk*.

A few important points are also necessary for the application of these probability models. In order to multiply (or exponentiate) probabilities, the probabilities must represent independent events. In this setting, this is only appropriate if the occurrence of occupational injuries in one year does not influence the probability of injury in subsequent years, so that the probabilities are constant over years. This is a fairly restrictive assumption; however, the model is often used even when time trends are present or other departures from the independence requirement are not too severe.

Poisson Probability Model

Another interpretation of the relative frequency measure, $\hat{p}$, is to consider it as an estimate of the *rate* at which injuries occur, taking the number of injuries, $D = 0, 1, 2, \ldots$, observed in a fixed time period and for a fixed number of workers "at risk", w, as having a Poisson distribution (Bailer, Reed, and Stayner, 1997). This requires that the assumptions of a Poisson process apply to injury incidence, requiring that (the probability of) the number of injuries in any time period is independent of (the probability of) the injury counts in other time periods (Hogg and Craig, 1995). As a consequence, both the mean and variance of D are estimated by $\hat{p}$ multiplied by the number of workers at risk, $\mu = \hat{p}w$ and $\sigma^2 = \hat{p}w$. The probability associated with the different injury counts are: $P(D = d) = ((\hat{p}w)^d \exp(-\hat{p}w))/(d!)$. Notice that, for $w = 1$ in any single year, $P(D = 0) = \exp(-\hat{p})$. Over a working lifetime, $P(D \geq 1) = 1 - P(D = 0)^{45} = 1 - \exp(-45\hat{p})$, which is a limit representation of the *working lifetime risk* provided by the Poisson probability model. The Poisson distribution is well known to be the limiting distribution for a binomial random variable with large n and small values for the binomial parameter, p (Hogg and Craig, 1995).

Given that injuries occur according to this probability model, interest is usually directed toward comparing different rate estimates based on different occupations, industries or other groups, $\hat{p}_i$, where the subscript i may be used to indicate different industries, occupations or other groups. The expected value for the number of injuries over a 45 year period, $\hat{p}_i \times 45$ years, may be shown to be an approximation of the *working lifetime risk* based on a Taylor series expansion of the $P(D = 0)^{45} = \exp(-45\hat{p})$.

Fortunately, comparison of group-specific rates does not require accurate characterization of the distribution. An approach, based on the empirical Bayes method, has recently been used for identification of elevated risks for different types of cancer in various occupations (Carpenter *et al.*, 1997). Another quantitative approach is to estimate the variance and derive confidence intervals for the working lifetime risk as a function of the individual group-specific rates (See and Bailer, 1998). Other methods may work well for identifying groups of industries and occupations with unusually high rates, *e.g.*, identifying as "high risk" those groups with estimated lifetime risk values greater than 1 death in 1000 working lifetimes and with a minimum of 5 deaths (Myers, Kisner, and Fosbroke, 1998).

Application of Life Table and Survival Analysis Techniques

Life table and survival analysis techniques (Klein and Moeschberger, 1997) have a long history of application in evaluating differences between groups using the survival function, $S(t) = P(T > t)$. For occupational injury risk assessment, the random variable T may represent a discrete, nonnegative random variable, representing the number of years worked until an event (fatal or nonfatal injury) occurs. Because there is no interest in events that occur prior to age 20 or beyond age 65, this is, more specifically, a left-truncated, right-censored survival function. If we consider the probability of death during the working lifetime of 45 years, $t_i = 1, \ldots, 45$, for $i = 1, \ldots, 45$, this is the complement of the event of surviving 45 working years, $P(45 \leq T) = F(t_i = 45) = 1 - S(t_i = 45)$. If $\hat{p}_i$ represents the probability of death in year t_i, then $1 - \hat{p}_i$ can be used to obtain an estimate of the survival function at year t_i. The nonparametric actuarial method for estimating the survival function is determined by the product of survival probabilities for all preceding years, $S(t_i) = \Pi_i(1 - \hat{p}_i)$, for $i = 1, \ldots, 45$. Now, $F(t_i) = 1 - S(t_i) = 1 - \Pi_i(1 - \hat{p}_i)$, which again is the *working lifetime risk* estimate.

Occupational injury studies are typically based on data obtained in accordance with *current life tables* rather than the long term *cohort* studies of a selected group more typical of occupational illness studies. If data were available on the exact ages at which fatal injuries occur, so that T is a continuous random variable, and a more specific determination of the numbers of workers at risk for injury at any given time, a more accurate estimate of $S(t)$ could be obtained using the product-limit or Kaplan-Meier estimate.

As an alternative to the nonparametric approach, a particular parametric form for the distribution of the continuous random variable, T, could be specified. The hazard function is useful in this regard: it is the ratio of the probability density to the survival function and represents the instantaneous probability of a fatal injury conditional on prior survival. The relative frequency estimate, $\hat{p}_i$, may be considered an estimate of the hazard, if the time until injury, T, is taken to have an exponential distribution, $P(t \leq T) = 1 - \exp(-\hat{p}t)$, with constant hazard equal to $\hat{p}_i$. Note that $P(45 \leq T) = 1 - \exp(-45\hat{p})$, which is equivalent to the limit representation of the *working lifetime risk* provided by the Poisson probability model. This result demonstrates that comparisons of the working lifetime risk are equivalent to comparing the 45-year survival probability for different occupations and industries using the exponential model.

The assumption of a constant hazard is not suitable for all survival data; therefore other parametric survival probability models allow more general hazard functions. Based on some knowledge of the change in hazard for injury with age, parametric models with a decreasing hazard, such as the Weibull distribution with a shape parameter < 1, could be useful in modeling situations where increasing experience on the job decreases a worker's risk over time. Occupations where hazards increase with loss of facility, as a result of aging, could be modeled by an increasing hazard, such as the Weibull distribution with a shape parameter > 1. This suggests another generalization of the working lifetime risk, $P(45 \leq T)=1 - \exp(-\hat{p} \times 45^{\eta})$ with the Weibull shape parameter η.

Survival analysis comprises a collection of methods that are powerful for the evaluation of subject-specific or group-specific covariate information with application to the problem of distinguishing the most hazardous occupations and industries. The location or scale of the Weibull distribution can be expressed as a function, $\hat{p}_i, = \exp(\beta Z_i)$, of a vector of individual worker-specific covariates, Z_i, and regression coefficients, β, as a further generalization of the working lifetime risk for comparison of different occupations and industries. The Cox (1972) proportional hazard regression method provides for the most powerful evaluation of covariate effects with an arbitrary nonspecified baseline hazard.

More sophisticated techniques, based on the use of *counting process* methods, permit the consideration of recurrent events especially important for the analysis of nonfatal injuries (Andersen *et al.*, 1993). Both marginal and conditional estimation methods, with new methods for variance estimation of regression coefficients, have been developed. These techniques permit different types of interpretation for the estimated covariate effects, which are useful in clinical studies, but the application of these methods for analysis of occupational injury data remains unexplored (Wei and Glidden, 1979). Recent developments (Wassell and Kulczycki, 1995; Wassell, Wojciechowski, and Landen,

1999) permit the modeling of repeated non-fatal injuries as recurrent events, to account for unobserved random effects in addition to observed covariates. These more advanced methods have greater data requirements and rely on cohort studies rather than more routinely collected census or survey data, which limit their application for occupational injury risk assessment.

SUMMARY

Probability models provide a useful and unifying framework for understanding the wide range of techniques and different interpretations of quantitative methods used for analysis of occupational injury data. Probability models specify a mechanism for the random occurrence of injuries after accounting for the deterministic effects of all measurable risk factors. The relative frequency estimate of the probability of injury has a different interpretation depending on the viewpoint of an individual worker, insurance claims estimator, or researcher interested in the probability applied to a large group of workers.

One metric, the *working lifetime risk*, is described using different probability structures which demonstrates that these definitions are complementary. The estimate of the working lifetime risk can be derived by considering the binomial random variable of the number of injuries, the geometric random variable indicating the number of years until a fatal injury occurs and, the nonparametric estimate of the survival function of the time until a fatal injury occurs. A limit form of the working lifetime risk is provided by considering a probability distribution of the number of events which occur from a Poisson process and the parametric exponential distribution of survival times. This limit form can be generalized by permitting greater flexibility in the hazard function, not restricting the hazard function to a constant. The inclusion of covariates, as a regression model representing the working lifetime risk, may overcome the restriction of the simpler methods which are an order invariant transformation of the fatality rates. More advanced survival analysis methods permit generalizing the concept of the working lifetime risk to permit recurrent (nonfatal) injuries.

Comparison of occupations and industries or other groups, for the purpose of identifying those at high risk, to establish research and intervention priorities, can be effectively accomplished using straightforward techniques. There are many advantages to using well known and studied statistical techniques for estimation and inference for the working lifetime risk. A better understanding of the probability mechanisms describing injury incidence, through examination of probability models, leads to an appreciation of the utility of standard statistical methods for analysis of occupational injury data.

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A General Framework For Prioritizing Research To Reduce Injuries And Diseases in Mining

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ABSTRACT

A strategy for prioritizing mining health and safety research by evaluating the potential for risk reduction through interventions is proposed. Mining has one of the highest incidence rates of injury and disease found in major industries. The main premise of this paper is that often the best opportunities to reduce these rates are not revealed by retrospective analysis of injury and illness data. Instead, a proactive approach is needed that accounts for risks to specific hazards that can be abated by engineering or behavioral interventions.

The process proposed here begins with development of prospective interventions. The degree of reduction in risk to be expected from an intervention then is determined from statistics on the mining worker population, the expected degree of success of the intervention, and the expected change in the severity of injuries resulting from the intervention. Three disparate mining health and safety concerns are presented to demonstrate common problems in assessing risks of injury and illness and describe additional data needs. Information on events preceding injuries and illnesses and more detailed demographic data on the mining work force are needed to analyze injury and illness data more precisely. Detailed information on exposure to specific hazards is necessary to evaluate the potential for an intervention to reduce risk of injury or illness.

Key Words: injury, illness, mining, risk assessment, prioritize

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INTRODUCTION

Recent initiatives such as the Government Performance and Results Act (GPRA) mandate directing research to achieving public goals. For the Office for Mine Safety and Health Research of the National Institute for Occupational Safety and Health (NIOSH), GPRA means directing research to reducing risks in mining.

Prioritizing research should do more than differentiate among risks to different populations. A proper strategy should also distinguish the degree to which risk is reduced. In this paper, a framework of risk analysis is proposed that considers the effectiveness of selected interventions in reducing mining health and safety problems.

There are many ways to conceptualize risk. Each concept is valid, and each is responsive to alternate objectives. In its purest form, risk is a function of the probability of the occurrence of a given undesirable event and the severity of the outcome of that event. Risk assessment can be used to assess changes in risk resulting from research interventions. This is a step that is often missing from a more formal framework, but is a key that ties risk assessment more closely with risk management.

Three mining research issues are examined to illustrate the proposed framework, to identify difficulties in comparing risks, and to identify data needs.

INJURY HAZARDS IN MINING

Mining has one of the highest incidence rates of injury and disease found in major industries. Hazards in mining include long-term problems, such as roof falls in underground mines, as well as emerging problems arising from changes in technology or changes in mining methods. Sprains and strains resulting from physically demanding work are common in mining, but are rarely life-threatening, whereas fires, explosions, and catastrophic collapses of underground mines occur much less frequently, but have the potential for killing many workers. Illnesses such as hearing loss and silicosis have significant permanent affects on the quality of life of miners.

The diverse nature of mining hazards and the resulting injuries and illnesses makes assessing risks difficult. Different frequencies of occurrence and different degrees of injury need to be compared in order to prioritize research based on risk. Estimates of time spent conducting specific tasks are necessary in order to evaluate the potential for interventions to reduce risk.

RISK ASSESSMENT OVERVIEW

Risk assessments can be used to make decisions on allocation of resources, setting and enforcement of regulations, inspection priorities, and, in the case addressed in this paper, setting research priorities. Methods of descriptive epidemiology are commonly used to compare injury incidence rates by place, time, and population. This information, in combination with a measure of the consequences of injuries, is a common basis for risk assessment.

Risk can be formally defined as the probability of an injury or illness multiplied by the severity of the health effect (McCormick, 1981; Brauer, 1990). Probability is usually expressed as the relative frequency of an event. Severity can be expressed in various ways, including by number of days lost, number of fatalities, medical cost, or a combination of these measures.

Problems in comparing injury risks arise because it is difficult to assess exposures to hazards or to compare the severity of a disabling to a temporary injury or a fatality to an injury. Proxies for exposure, such as total employment in a given industry or occupation, are usually substituted when exposure to specific hazards is not known. However, exposure, defined as the actual time involved in a specific hazardous task, is needed to evaluate the potential degree of risk reduction resulting from proposed interventions. Surveys to characterize occupations, equipment use, and injury and illness incidence rates in greater detail are needed in addition to analyses of actual time worked at different hazardous tasks.

Workers, engineers, or other interested parties (referred to here as stakeholders) assess risks by implicitly considering factors such as value, benefit, feasibility, and acceptance. These qualitative perceptions are invaluable for identifying strategies for reducing risk. Therefore, stakeholders are an important source of input in selecting interventions to be evaluated in a quantitative risk assessment.

AVAILABLE DATA FOR ADDRESSING MINING INJURY HAZARDS

The primary source of injury data for the U.S. mining industry is the "Mine Accident, Injury, and Illness Report" that is submitted to the Mine Safety and Health Administration (MSHA). This information is required under Title 30, Part 50, of the Code of Federal Regulations for every mining accident, injury, or illness. Information in these reports includes commodity, location, information on the injured person, job title, source and nature of the injury, machinery involved, and severity of an injury. Severity of injury is based on whether a fatality, a disabling injury, or lost days occurred. A complimentary report, "The Quarterly Mine Employment and Coal Production Report," is a source of data on mine location and worker employment corresponding to those mines reporting accidents, injuries or illnesses. Information from each of these sources is compiled by MSHA into accident-injury-illness and address-employment files for both operators and contractors. Data from the address-employment files provide employment totals to the level defined by commodity class and location, such as underground nonmetal or surface coal.

Errors in the MSHA accident and employment files arise because of misclassification of information submitted. Such errors need to be considered in any analysis of these data. Other, more significant limitations on the use of MSHA data in risk analysis are that information on causes is insufficiently described and that detailed exposure data are not available. Only the immediate circumstances associated with an incident are listed, and no reference is given to preceding events or contributing factors. Exposure data are only available by location and not for specific tasks or even for job title or type of machinery used. As mentioned previously, more detailed exposure data are necessary to evaluate the potential for risk reduction from interventions.

Ongoing research is addressing shortcomings in the usefulness of MSHA injury data for risk assessment. An injury database used in Australia that includes events and conditions that precede injuries is being evaluated at the Spokane Research Laboratory (Feyer and Williamson, 1997). The Pittsburgh Research Laboratory is designing a population survey similar to one conducted in 1986 by the former U.S. Bureau of Mines (Butani and Bartholomew, 1988) to obtain the demographic data necessary for conducting a detailed analysis of injury incidence rates.

RISK REDUCTION

Risk assessments do not sufficiently emphasize the impact of research interventions on health and safety risks. The process described here begins by developing prospective interventions using injury data, stakeholder input, or the results of task analyses or time studies. Task analysis is a process of describing interactions among workers and machinery or other work systems. Task analyses can be used to identify potential hazards, estimate exposure to specific hazards, and develop interventions. Time studies are conducted by timing the duration of different work tasks. The results of time studies can be used to estimate exposure to specific hazards and to evaluate the impact of proposed interventions.

The overall effect of an intervention on population risk can be characterized by the population incidence rate, the fraction of the population exposed, an average of the proportion of time exposed to the hazard addressed by the intervention, and the effectiveness of the intervention at abating the hazard. An intervention may also reduce risk by reducing the severity of an injury because risk is a function of both the probability of occurrence and severity. Therefore, the degree of reduction in risk to be expected from an intervention can be calculated as the product of the population incidence rate, the fraction of the mining population affected by the intervention, the expected degree of success of the intervention, and the expected change in the severity of injuries resulting from the intervention.

EXAMPLES AND DATA NEEDS

Three examples of current health and safety problems and possible interventions are described to demonstrate the difficulties encountered when evaluating the degree of risk reduction expected for a range of research alternatives. The example problems and interventions are (1) reducing strains and sprains to rock drillers by reducing the weight of jackleg drills, (2) reducing noise-induced hearing loss in rock drillers by modifying jumbo drills, and (3) reducing fatalities in open-pit mines by improving methods for designing slopes to prevent slope failures.

Jackleg Drillers

The jackleg drill is a portable, air-operated drill used in underground hard-rock mines. It weighs approximately 100 pounds. Back sprains or strains to jackleg operators account for 30% of the reported injuries to rock drillers that resulted in time lost from work. Reducing the weight of the jackleg drill by as much as 50 pounds could reduce the number of back injuries and possibly the amount of time lost because of back injuries (McKibbin, 1998, personal communication). One means of reducing weight is to use lighter weight materials. However, reducing the weight of a jackleg drill might result in an increase in vibration and lead to other injuries. One hypothesis is that most back injuries to jackleg drillers occur while the miner is moving the drill. Information relating injuries to specific tasks is needed to assess this hazard in more detail, such as the relationship between weight reduction and the incidence of back sprains and strains, the number of employees exposed to this particular lifting hazard, and the amount of time spent at the specific task of moving the drill or drilling. Occupational survey data or a task analysis are needed as well as a calculation of the relationship among weight reduction, back injury incidence, and days lost per incident.

Jumbo Drillers

Modifications to another type of drill, the jumbo drill, are proposed to reduce noise-induced hearing loss in rock drillers. The decrease in excess risk of hearing impairment can be predicted for the expected level of noise reduction achieved by the modifications (NIOSH, 1972). The primary difficulty in comparing the degree of risk reduction for jackleg drillers by using lighter weight materials and for jumbo drillers by reducing noise levels is how does one compare the severity of the injury? MSHA uses a conversion of 600 work days lost for partial hearing impairment and 3,000 work days lost for total hearing loss for the purpose of comparison to lost-time injuries. This conversion is based on a schedule of time charges established by the American National Standards Institute. To relate 600 work days lost for partial hearing loss to a jumbo driller to actual work days lost by a jackleg driller relies on value judgments. The objectivity of the risk assessment is reduced as a result. As in the first case, the number of jumbo drill operators and the duration of time spent at specific tasks are needed to calculate risk reduction. A task analysis or a time study is needed along with noise surveys to develop interventions that address specific activities where exposure is greatest.

Slope Failure

Injuries associated with slope failures are relatively rare. However, when they occur, they often result in fatalities. Probabilistic modeling methods can improve slope design and reduce unanticipated failures by estimating the probability of slope failure and then the reduction in risk of failure resulting from a design change. A reduction in the risk of slope failure can be used to estimate the expected reduction in the probability of a fatal injury. For comparative purposes, MSHA assigns 6,000 days lost to a fatality. As in the previous two cases, detailed information on the number of employees exposed and the amount of time spent in specific tasks are the primary missing components needed to evaluate risk reduction.

DISCUSSION AND CONCLUSIONS

Data available from MSHA can be analyzed to identify when and where injuries happen and, in a general sense, the relative risk to different populations. This is a necessary starting point; however, often the best opportunities to reduce risks are not revealed by analyses of injury statistics. The MSHA data do not address the causes of or circumstances leading to injuries, nor do they provide an assessment of risks related to specific event sequences preceding injuries. Most importantly, the potential for successful intervention strategies is ignored.

A full consideration of risk is necessary to determine the potential for reducing risk. Such a consideration requires detailed information on exposure to specific hazards and consideration of how injury severities are compared. The nature of injury hazards is diverse, and no single method can measure absolute risk objectively. Value judgments are always necessary. Consequently, the emphasis in risk assessment of mining injuries should be on incremental improvements in risk reduction by research interventions.

A risk reduction framework also facilitates objective measurement of research results as mandated by GPRA. Measurement of absolute reductions in injury incidence is rarely possible. However, criteria based on intervention design measures can be related to risk reduction. For example, design measures in the three examples could be weight reduction achieved for the jackleg drill, noise reduction achieved for the jumbo drill, and reduction of uncertainty in slope design. Relative impacts can be estimated based on risk reduction.

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Lifetime Risk of Fatal Occupational Injuries within Industries, by Occupation, Gender, and Race

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ABSTRACT

Estimates of risk accumulated over a working lifetime are used to assess the significance of many workplace health hazards. Most studies which have estimated this risk have focused on a worker's lifetime risk of dying of a stated illness based on exposure to a hazard in a specific job. The concept, however, has not been widely applied to occupational injury deaths. This study examines the use of lifetime risk based on national fatal injury data from the Bureau of Labor Statistics (BLS) Census of Fatal Occupational Injuries (CFOI). Lifetime risks are defined by specific causal events for those groups identified as having the highest general lifetime risks. The lifetime risk model for injury used in this work can be compared with risk assessments for occupational illnesses. Fatal injury lifetime risk estimates will be useful in defining traumatic injury exposures that are appropriate for targeting research and prevention efforts needed to reduce the burden of work-related death within the United States. These estimates also provide a means of prioritizing traumatic injury research with fatal illness research, while providing the additional benefit of providing a means of informing workers of their fatal injury risks.

Key Words: occupational injury death, cause of death, high-risk job

INTRODUCTION

Estimates of risk accumulated over a working lifetime are used to assess the significance of many workplace health hazards. Most studies that have esti-

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mated this risk have focused on a worker's lifetime risk of dying of a stated illness based on exposure to a hazard in a specific job (Palmer and Rickett, 1992; Nurminen *et al.*, 1992; Stayner *et al.*, 1992; Smith and Stayner, 1990; Hodgson and Jones, 1990). The concept, however, has not been widely applied to occupational injury deaths. A recent study done by Fosbroke *et al.* (1997) did estimate the average lifetime risk of work-related fatal injuries. The results from the study suggest that, when lifetime risk is considered for traumatic injuries, the risks for specific causes of death for certain occupations are of the same magnitude as cancer risks reported for specific occupational exposures. Based on these findings, risk assessment for traumatic causes of death should be considered equally with risk assessments for certain health exposures.

The purpose of this work was to build upon the recent study done by Fosbroke *et al.* (1997). The current study examined the use of lifetime risk based on national fatality data from the Bureau of Labor Statistics (BLS) Census of Fatal Occupational Injuries (CFOI). The objectives of the study were to define the general lifetime risk of occupational injury death within detailed industry and occupation combinations by gender or race; and to define cause-related lifetime risks for those groups identified as having the highest general lifetime risks. As in the previous study, this paper used a lifetime risk model for injury that can be compared with risk assessments for occupational illnesses.

METHODS

Occupational fatality data were extracted from the BLS CFOI for the years 1992 through 1996. The CFOI data include information on fatal work injuries occurring in the 50 states and the District of Columbia. The BLS uses multiple data sources to identify and verify these fatal work injuries. Information about each workplace fatality, such as occupation at the time of death and other worker characteristics and circumstances of the event, is obtained by cross-referencing source documents, including death certificates, workers' compensation records, and reports to Federal and State agencies (Toscano and Windau, 1997).

The detailed industry and occupation information in the CFOI data were coded using the Bureau of the Census (BOC) 1990 classification system (Bureau of Census, 1992). Denominator data were obtained from the 1992 through 1996 Current Population Survey (CPS) monthly employment files (Bureau of Labor Statistics, 1992).

The working lifetime risk was calculated using the same formula from the previous study:

$$\mathrm{WLTR} = \left[1 - (1 - \mathrm{R})^{y}\right] \times 1000$$

where WLTR = Working Lifetime Risk; R = Ratio of the average annual number of work-related fatal injuries among workers of a given group to average annual employment in that group; y = Years of exposure to work-related fatal injury risk.

The formula assumes R, which is a weighted average of deaths across all workers employed within a specific group, provides an unbiased measure of the risk for the group, on a population basis. R is equal to the average annual fatality rate for a specific group expressed as a simple proportion, rather than in units of some fixed number of exposed workers. The formula also assumes that the corresponding lifetime risk estimate is for a fixed initial population of 1000 workers. This means that the population at risk decreases with time (*i.e.*, the number of estimated deaths in year one are removed from the original starting population, and the number of deaths estimated for year two are based on the estimated number of survivors, and so on).

The value of R was estimated using all five years of data from the CFOI and the CPS. This was done to provide a more stable estimate of R for each group. The value of y was set at 45 years, as recommended by the Occupational Safety and Health Administration (OSHA) (1995) and Stayner (1992). The current study only included data for workers aged 20 through 64. This was done to better define worker risk during the defined 45-year working lifetime. The current study examines characteristics of the fatality based on the BLS Occupational Injury and Illness Classification System (OIICS) (National Safety Council, 1997). The OIICS includes five classification structures that describe the injury and how it occurred: nature of injury, part of body affected, source of injury, event or exposure, and secondary source of injury. Specifically, the current study examines the event or exposure which describes the manner in which the injury was sustained. This differs from the study done by Fosbroke *et al.* (1997), which examined cause of death characteristics by E-codes (E800–E999) found in the International Classification of Diseases, 9th Revision (World Health Organization, 1977). E-codes can be viewed as a combination of the event and source codes from the OIICS. To be included in this report, a minimum of five deaths was required for the calculation of a lifetime risk estimate, and the estimate had to be greater than one death per 1000 working lifetimes.

RESULTS

Demographics of Fatal Injuries

During the 5-year period, 1992 through 1996, there were 28,068 fatal occupational injuries in the United States according to the CFOI. Ninety two percent of these deaths were to male workers. Whites (excluding Hispanics) accounted for 73.5% of the worker fatalities, 10.7% were to African-American (excluding Hispanics) workers, and 9.9% were to Hispanic workers. An additional 3.9% were to workers of other races. The remaining 2% of deaths were among workers for whom race was unknown.

The five industries with the highest 5-year average annual fatal injury rates were logging (148 deaths, 112.4 deaths/100,000 workers), fishing, hunting and trapping (78 deaths, 99.6 deaths/100,000 workers), taxi cab services

(97 deaths, 95.3 deaths/100,000 workers), coal mining (57 deaths, 48.6 deaths/100,000 workers), and water transportation (70 deaths, 42.6 deaths/100,000 workers). The four occupations with the highest average annual fatal injury rates were sailors (151 deaths, 177.6 deaths/100,000 workers), loggers (535 deaths, 158.1 deaths/100,000 workers), airplane pilots (622 deaths, 146.6 deaths/100,000 workers), and fishers (304 deaths, 144.5 deaths/100,000 workers).

The major event category that had the greatest number of deaths was transportation incidents, accounting for 40% of these fatal injuries. Other major event categories accounting for at least 2500 deaths were assaults and violent acts (20%), contact with objects and equipment (16%), falls (10%), and exposure to harmful substances or environments (10%). Two detailed event categories accounted for nearly a quarter of the fatal injuries—assaults and violent acts by shooting (14%) and highway collisions between motor vehicles or equipment (10%).

The number of deaths and the lifetime risk estimate are shown in Tables 1 through 6 for specific events occurring to workers of specific occupations within industries. Shown are the ten to fifteen combinations with the highest lifetime risks. Tables 1 and 2 provide results by gender. Tables 3 to 6 provide results for the following: white workers (excluding Hispanics); African-American workers (except Hispanics); Hispanic workers; and workers of other races. In all tables, the lifetime risk estimate is expressed as the number of deaths in 1000 45-year working lifetimes. For the female and other race categories, there were fewer than 15 combinations meeting our criteria of having a minimum of 5 deaths during the five year period and having a lifetime risk of at least 1.0 in 1000.

Gender

Table 1 provides the 15 combinations with the highest lifetime risks for male workers. The number of deaths ranged from a low of 10 to a high of 323. Three high-risk combinations had lifetime risk estimates greater than 100/1000 working lifetimes. An examination of the industries in Table 1 shows a clustering of risk around common, or similar work environments. Three high-risk groups were associated with logging, three were related to fishing or water transportation, and two were aircraft related. Four event categories were found to be the cause of death in more than one combination of industry and occupation: being struck by falling objects, homicides by shooting, boats sinking, and airplane crashes.

To better understand the circumstances of these high-risk events, other data elements, such as the narrative injury description, were reviewed for selected industry, occupation, and event combinations. Among male workers, the highest lifetime risk estimate was for airplane pilots in agricultural services killed in airplane crashes. Of the 62 deaths in this category, the narratives indicate that nearly all were associated with commercial spraying, or crop dusting. Athletes in business services, n.e.c. who died by drowning were prima-

Table 1. Highest 45-year working lifetime risks for male workers by industry, occupation, and cause of death, 1992–1996. The leading lifetime risk estimates are only presented for combinations that had a minimum of 5 deaths during this 5-year period.

Industry	Occupation	Event	Deaths	Lifetime risk[a]
Agricultural services	Airplane pilots	Airplane crashes	62	308.9
Grocery stores	Sales counter clerks	Homicide by shooting	14	147.6
Business services, N.E.C.	Athletes	Drowning	11	106.6
Air transportation	Airplane pilots	Airplane crashes	291	59.1
Logging	Logging supervisors	Struck by falling objects	31	55.8
Administration of Environmental Quality and Housing Programs	Firefighters	Forest/outdoor fire	10	54.5
Taxi cab service	Taxi cab drivers	Homicide by shooting	323	50.8
Logging	Loggers	Struck by falling object	304	43.1
Fishing/hunting/trapping	Captains of vessels	Boat sinking	31	38.2
Eating/drinking places	Guards (private)	Homicide by shooting	37	31.2
Water transportation	Sailors	Fall from ship	32	28.4
Personnel supply services	Truck drivers	Highway collision other vehicle	15	28.4
Logging	Sawing machine operators	Struck by falling objects	12	28.2
Fishing/hunting/trapping	Fishers	Boat sinking	106	24.3
Construction	Elect. power installers	Contact with overhead power lines	20	19.6

[a] Lifetime risk are in units of deaths per 1000 45-year working lifetimes.

Table 2. Highest 45-year working lifetime risks for female workers by industry, occupation, and cause of death, 1992–1996. The leading lifetime risk estimates are only presented for combinations that had a minimum of 5 deaths during this 5-year period.

Industry	Occupation	Event	Deaths	Lifetime risk[a]
Trucking services	Truck drivers	Highway noncollision	17	5.6
Air transportation	Public transport attendants	Airplane crashes	28	5.4
Construction	Construction laborers	Pedestrian struck by vehicle in roadway	13	5.4
Trucking services	Truck drivers	Highway Collision other vehicle	13	4.3
Trucking services	Truck drivers	Collision stationary object on side of road	12	3.9
General gov, N.E.C.	Office clerks	Homicide by violence N.E.C.	5	3.8
Direct sales estab.	News vendors	Highway collision other vehicle	5	3.5
Eating/drinking places	Supervisors/proprietors	Homicide by shooting	5	3.4
Newspaper pub/printing	News vendors	Highway collision other vehicle	6	2.2
Laundry, cleaning, garment services	Sales counter Clerks	Homicide by shooting	6	1.3
Gas service stations	Cashiers	Homicide by shooting	8	1.3
Grocery stores	Supervisors/proprietors	Homicide by shooting	28	1.1
General gov, N.E.C.	Secretaries	Homicide by violence N.E.C.	5	1.0
Agricultural crops	Farm workers	Off road noncollision	6	1.0

[a] Lifetime risk are in units of deaths per 1000 45-year working lifetimes.

Table 3. **Highest 45-year working lifetime risks for white workers, excluding Hispanics, by industry, occupation, and cause of death, 1992–1996. The leading lifetime risk estimates are only presented for combinations that had a minimum of 5 deaths during this 5-year period.**

Industry	Occupation	Event	Deaths	Lifetime risk[a]
Agricultural services	Airplane pilots	Airplane crashes	59	310.0
Business services, N.E.C.	Athletes	Drowning	11	104.9
Air transportation	Airplane pilots	Airplane crashes	285	77.6
Administration of environmental quality and housing programs	Fire fighters	Forest/outdoor fire	14	73.4
Logging	Logging supervisors	Stuck by falling objects	27	48.8
Taxi cab services	Taxi cab driver	Homicide by shooting	120	40.7
Logging	Loggers	Struck by falling objects	236	40.1
Fishing/hunting/trapping	Captain of vessels	Boat sinking	25	35.8
Grocery stores	Sales counter clerks	Homicide by shooting	13	33.5
Personal supply	Truck drivers	Highway Collision. other vehicle	12	33.5
Construction	Elect. power installers	Contact with overhead power lines	18	23.3
Fishing/hunting/trapping	Fishers	Boat sinking	83	20.8
Water transportation	Sailors	Fall From Ship	19	19.0
Construction	Elect. power installers	Contact wiring, transformers	12	15.6
Saw mills	Loggers	Struck by falling objects	10	14.3

[a] Lifetime risk are in units of deaths per 1000 45-year working lifetimes.

Table 4. **Highest 45-year working lifetime risks for African-American workers, excluding Hispanics, by industry, occupation, and cause of death, 1992–1996. The leading lifetime risk estimates are only presented for combinations that had a minimum of 5 deaths during this 5-year period**

Industry	Occupation	Event	Deaths	Lifetime risk[a]
Eating/drinking estab.	Guards (private)	Homicide by shooting	16	107.0
Taxi cab services	Taxi cab drivers	Homicide by shooting	137	66.7
Logging	Loggers	Struck by falling objects	56	58.4
Construction	Roofers	Fall From roof	13	8.1
Grocery stores	Supervisors/proprietors	Homicide by shooting	30	7.2
Trucking services	Truck drivers	Highway Collision other vehicles	56	6.3
Trucking services	Truck drivers	Highway Noncollision	52	5.8
Taxi cab services	Taxi cab drivers	Highway Collision other vehicles	10	5.0
Trucking services	Truck drivers	Highway collision stationary obj. on side of the road	42	4.7
Gas service stations	Cashiers	Homicide by shooting	6	4.5
Protective services	Guards (private)	Homicide by shooting	41	4.5
Agricultural crops	Farm workers	Off road noncollision	13	4.3
Grocery stores	Cashiers	Homicide by shooting	32	4.1
Public Safety	Police (public)	Homicide by shooting	29	4.0
Construction	Operating engineers	Off road noncollision	5	3.8

[a] Lifetime risk are in units of deaths per 1000 45-year working lifetimes.

Table 5. Highest 45-year working lifetime risks for Hispanic workers by industry, occupation, and cause of death, 1992–1996. The leading lifetime risk estimates are only presented for combinations that had a minimum of 5 deaths during this 5-year period

Industry	Occupation	Event	Deaths	Lifetime risk[a]
Taxi cab services	Taxi cab driver	Homicide by shooting	46	49.5
Gas service stations	Cashiers	Homicide by shooting	12	13.1
Grocery store	Supervisors/proprietors	Homicide by shooting	52	12.2
Protective services	Guards (private)	Homicide by shooting	31	9.5
Construction	Roofers	Fall from roof	33	8.5
Eating/drinking places	Bartenders	Homicide by shooting	9	7.1
Grocery store	Cashiers	Homicide by shooting	37	6.0
Direct sales estab.	Door-to-door salesmen	Homicide by shooting	15	5.9
Trucking services	Truck drivers	Highway Noncollision	33	5.8
Trucking services	Truck drivers	Highway collision other vehicle	28	4.9
Public order	Police (public)	Homicide by shooting	19	4.6
Trucking services	Truck drivers	Highway collision stationary obj. on side of the road	26	4.6
Agricultural services	Farm workers	Off-Road Noncollision	8	3.0
Construction	Electricians	Contact with wiring, transformers, etc...	7	2.9
Automotive repair	Auto body repairers	Homicide by shooting	6	2.8

[a] Lifetime risk are in units of deaths per 1000 45-year working lifetimes.

Table 6. **Highest 45-year working lifetime risks for workers of other races, excluding Hispanics, whites, and African-Americans, by industry, occupation, and cause of death, 1992–1996. The leading lifetime risk estimates are only presented for combinations that had a minimum of 5 deaths during this 5-year period.**

Industry	Occupation	Event	Deaths	Lifetime risk[a]
Fishing/hunting/ trapping	Fishers	Fall from ship	14	41.7
Gas service station	Service station occup.	Homicide by shooting	14	36.7
Taxi cab services	Taxi cab drivers	Homicide by shooting	26	33.2
Liquor stores	Supervisors/proprietors	Homicide by shooting	16	30.0
Grocery stores	Supervisors/proprietors	Homicide by shooting	90	24.9
Grocery stores	Cashiers	Homicide by shooting	58	16.8
Grocery stores	Stock handlers/baggers	Homicide by shooting	9	6.1
Trucking services	Truck drivers	Highway collision stationary obj. on side of the road	5	4.3
Trucking services	Truck drivers	Highway noncollision	5	4.3
Grocery stores	Supervisors/proprietors	Homicide by stabbing	5	1.4

[a] Lifetime risk are in units of deaths per 1000 45-year working lifetimes.

rily commercial divers (1 case was inconclusive). All 10 deaths of firefighters by forest or outdoor fires in the Administration of Environmental Quality and Housing Programs industry appeared to be associated with a single event. Finally, the guards in eating/drinking establishments classified as homicide by shooting appear to be guards in bars (*e.g.*, bouncers, doormen).

The high-risk groupings for female workers were different from those for male workers (Table 2). Only two combinations that occurred among the high-risk male groups also occurred among females: homicides by shooting in eating/drinking places and homicides by shooting in grocery stores. Even here, the occupational classifications were slightly different, with females being classified as proprietors/supervisors, while males were guards and sales counter clerks, respectively. The number of deaths for these fourteen high-risk groups of female workers ranged from a low of 5 deaths to a high of 28 deaths. The highest lifetime risk estimate for female workers was 5.6 per 1000 working lifetimes. Homicide by shooting, highway collisions with other vehicles, and homicide by violence n.e.c., were the event categories that appeared in more than one occupation by industry combination for female workers.

Among female workers, two high-risk combinations accounted for 10 deaths in the industry category of general government, n.e.c. Five were secretaries and five were office clerks. All 10 were due to homicide by violence n.e.c., and appeared to be associated with a single event. Of the 13 deaths among female construction laborers due to being struck by vehicle in roadway, 6 were working as flaggers, 10 were struck by motor vehicles, and 3 were struck by equipment in the work zone.

Race

The risk profile for white workers (Table 3) was similar to the risk profile for male workers. Air crashes among airplane pilots in air transportation and drowning among athletes in business services, n.e.c. again had life time risk estimates greater than 100 in 1000. Among African-American workers (Table 4), private guards employed in eating and drinking establishments, who were killed by homicides due to shootings, had a lifetime risk estimate greater than 100 in 1000. No lifetime risk estimates for Hispanic workers (Table 5) or workers of other race (Table 6) exceeded 100 in 1000.

Some combinations of industry, occupation, and event were among the highest lifetime risks for two or more racial categories. For example, homicide by shooting among taxi drivers in taxi cab services was a high-risk event for all four racial categories with lifetime risk estimates varying from a low of 33.2 for workers of other races to a high of 66.7 for African-American workers. Being struck by falling objects among loggers in the logging industry was a high-risk event for white and African-American workers, where lifetime risk estimates were 40.1 and 58.4, respectively. Four injury hazards were identified among the high lifetime risks for African-American and Hispanic workers, as well as workers of other races. Two involved homicide by shooting in grocery stores where the victim was either a supervisor/proprietor or a cashier. The other two involved highway collisions with a stationary object on the side of roadway or a highway noncollision incident. Truck drivers in trucking services were the victims in both of these transportation events.

DISCUSSION

This analysis of fatal occupational injury provides a priority list for research and intervention efforts to better understand and reduce workplace fatalities. Traditionally, occupational injury research has been based on the univariate analysis of industry, occupation, and cause of death, or by combining these variables in broad categories. While these analyses have been useful in identifying major areas that required further research, they tend to mask high-risk groups. Risks do differ by race or gender categories within detailed industry and occupation classification systems. To better define these differences, this work has identified the highest fatal injury risks in United States' workplaces for those race and gender categories exposed to specific fatal injury events using detailed industry and occupation classification systems.

By focusing on event, occupation, and industry combinations that had the greatest lifetime risk, we have confirmed earlier targeted reports on some high-risk groups and identified some previously unidentified groups. Risks to loggers in the logging industry have been reported by NIOSH previously (Myers and Fosbroke, 1994; Braddee, 1994). Risks to taxi cab drivers have also been reported previously (Castillo and Jenkins, 1994; Toscano and Windau, 1997). Finally, fatality concerns for commercial fishermen have been documented (Bender, 1994; Conway, 1994; Kennedy, 1994). Risks that have not been previously reported include commercial divers, commercial crop dusters and aerial spraying pilots, as well as African-American males who work as bouncers for eating and drinking establishments.

The ranking of the industries with the five highest lifetime risk estimates in this study was identical to a prior analysis conducted using the National Traumatic Occupational Fatalities (NTOF) data (Fosbroke *et al.*, 1997). However, due to CFOI's more complete capture of work-related fatal injuries, the lifetime risk estimates presented in this paper are higher. In terms of occupation, two occupations (structural metal workers and extractive occupations) were among the top five in the NTOF lifetime risk analysis, but not among the top five in the CFOI analysis. In the prior study, sailors and deck hands were combined into a single occupation group called water transport occupations because of the use of printed employment estimates from the BLS. In this current study, estimates are given for each occupation separately because detailed employment data, maintained by BLS in an electronic format, were used.

Results by gender and race categories define risks faced by specific subgroups of the U.S. workforce. The results for females indicate that, while they do not have lifetime risk estimates as high as those for males, there are still 14 occupations within industries that meet or exceed what OSHA considers a significant lifetime risk, 1 death per 1000 working lifetimes (Adkins, 1993).

Lifetime risks by racial groups are also valuable, not only to verify that specific occupations have high risks across all racial groups (*e.g.*, taxi cab drivers, truck drivers, loggers, fishermen), but also to identify specific injury risks for minority racial groups. These race- and gender-specific lifetime risks allow public health professionals and researchers to better target research and prevention efforts in these more defined populations.

This analysis of CFOI data underscores the necessity for maintaining narrative data describing injury events, as well as data such as the day of week, the year of injury, and other descriptive variables. Through examination of these additional fields, it was possible to identify airplane pilots in agricultural services as being commercial applicators, or crop dusters. These variables were also useful for identifying multiple fatality events, such as those of government workers in an apparent single act of violence and those of the fire fighters in an apparent single wildland fire.

Though these multiple fatality events might be discounted as aberrations, readers should be careful in assuming that they are without merit. The death of 14 fire fighters (10 of them males) in a single fire accounts for why this group is on the table of high-risk injury exposures, but such multiple fatality events for wildland firefighters are not unprecedented. In 1953, the Rattlesnake fire in the Mendocino National Forest took the lives of 15 firefighters (Isner and Baden, 1995). These two tragic events are separated by a span of 41 years, which is contained within the 45-year working lifetime defined for this paper. Also during this 41-year time period, a third wildland fire claimed the lives of 12 fire fighters in 1966 (Williams, 1995). Thus, while the lifetime risk presented for these fire fighters is likely too high due to chance, the occurrence of three such events in 41 years would still suggest a risk of over 20 deaths per 45-year working lifetimes. This high-risk for wildland fire fighters also suggests that periodic major disasters may be very influential in evaluating the lifetime risk of certain occupations. Based on this, it is possible that this study missed other high-risk groups that are associated with periodic multiple fatality events (*e.g.*, coal miners and mine explosions).

For this study, we assumed a working lifetime of 45 years starting at age 20. The exclusion of workers less than 20 years of age and those greater than age 65 years of age does have implications for the estimation of lifetime risk. First, since the lifetime risk formula is a power function, extension of working lifetime beyond 45 years would naturally increase the expected number of deaths per 1000 working lifetimes. Second, based on prior studies of fatal occupational injury (Kisner and Pratt, 1997; Toscano and Windau, 1997), work-related fatal injury rates are greater for workers over age 65 than for workers age 20 to 65. This is especially true for some specific worker populations, such as agricultural workers (Myers and Hard, 1995). Thus, if older workers were included in the lifetime risk calculations, the ranking of specific injury hazards could change from those reported here. However, restricting the ages for estimating lifetime risks does allow for a better estimate of risk for the predominate age period when most individuals are working. The 20 to 64 age group does show the most consistency in their hours worked (Ruser, 1998). This age range also more closely follows the typical working lifetime and age range considered by others who conduct research on occupational exposures to health hazards (Stayner, 1992).

There are other issues related to the selection of data sources in this study. For example, the CFOI uses the Standard Industrial Classification (SIC) system (Office of Management and Budget, 1987) for categorizing industry, while the CPS uses the Bureau of the Census (BOC) industry classification system. The SIC codes are more specific than the BOC codes and can be collapsed into the BOC categories. This precludes the calculation of lifetime risk estimates for detailed SIC industry categories, such as those under the construction industry. The CFOI also uses the Occupational Injury and Illness Classification System (OIICS) to describe the injury event, rather than the International Classification of Diseases-Ninth Revision (ICD-9), E-Code. Therefore, the injury risks described by this study differ somewhat from risks reported based on E-Codes (Fosbroke *et al.*, 1997; Jenkins *et al.*,1993).

Some of the industry and occupation combinations that have the highest lifetime risks are relatively small in terms of employment. This includes white pilots in agricultural services (approximately 1600 workers), male sales clerks in grocery stores (approximately 800 workers), male commercial divers in business services n.e.c. (approximately 900 workers), African-American guards in eating and drinking establishments (approximately 1300 workers), white wildland firefighters (approximately 1700 workers), and male logging supervisors in logging (approximately 4900 workers). To some extent, these lifetime risk estimates may be less stable compared to those estimates presented where employment is substantially higher, both because of the employment estimates used to calculate the lifetime risks, and because of annual variations in the number of fatalities occurring to such groups. This would result in higher variance estimates for these low employment groups. Still, many of these groups with low employment show high numbers of fatalities (*e.g.*, pilots in agricultural services at 62 deaths, logging supervisors at 31 deaths) to justify their consideration as a major concern. In addition, high-risk occupations within industries tend, in general, to be associated with low employment. Only six of the combinations identified on Tables 1 through 6 represent an "occupation within industry" annual employment above 60,000 workers (male loggers within logging, female proprietors or supervisors in grocery stores, African-American truck drivers in trucking services, African-American private guards in protective services, African-American cashiers in grocery stores, and African-American public police in public safety).

The use of the CPS as an employment source also creates some limitations in the estimation of lifetime risks. Because of the nature of the CPS, lifetime risks calculated here were based on the workers primary industry and occupation. This may cause some under estimation of the number of workers employed in certain industries or occupations, especially if they are jobs that are part-time or seasonal in nature. In addition, there may be certain occupations that are more difficult to assess using a household survey. For example, employment in the fishing industry may be under estimated by the CPS based on an independent employment estimate for the State of Alaska in 1991 (Conway, 1994). Conway reported an annual average of 18,000 workers in the Alaska fishery in 1991, while the CPS reported an estimate of approximately 3300 workers for the same year. It is unclear whether this discrepancy in fishing employment only occurs in the State of Alaska, or is a common undercount in all States in the CPS. If this magnitude of under estimation does occur nationally, then the lifetime risks presented here for the fishing industry would be dramatically overestimated. The extent to which other occupations are under reported in the CPS is hard to document. Despite these limitations in the CPS, no other data source is available that allows for the calculation of employment by industry and occupation on an annual basis in the United States.

Finally, when examining the lifetime risks presented in this paper, it is important to remember that the risk estimates are for a population of individuals, not a single individual. In addition, the estimates rely on a pooled estimate of risk for all workers between the ages of 20 and 64 years. Thus, estimates for risk for an individual worker, or group of workers of differing ages are not addressed in this approach. While it would be possible to use this technique to define the risk of workers for a portion of their working life within a given industry and occupation, or to develop a risk estimate for an individual who moves through different jobs during a working lifetime, such an approach would not be practical when comparing occupations and industries, gender, or race. By making these comparisons based on a fixed set of criteria, these comparisons become more meaningful from a public health perspective.

CONCLUSIONS

The use of lifetime risk estimates in assessing the risk of traumatic fatal injuries to specific occupations employed within specific industries is a useful means for both prioritizing occupational injury concerns nationally, and in gauging the relative risks workers face from fatal injuries with respect to occupational health. The results of this work clearly show the usefulness of considering lifetime risk when defining the seriousness of a specific type of fatal event for a defined occupation within an industry.

The results presented here do show many consistencies with previous occupational fatality studies defining high-risk occupations or industries. This work, however, provides new insight on high-risk occupations within industries that, while understandable when looked at carefully, have not been clearly identified in previous literature. Lifetime risk estimates, such as those for male airplane pilots working in the agricultural services industry, strengthen the position that working lifetime risks to occupational fatal injuries pose a major public health threat for certain workers, and that fatal injury risk assessment is of equal importance to occupational health risk assessment when prioritizing ways of improving the health and safety of U.S. workers. Finally, these lifetime risk estimates may play a useful role in assisting the public health community in notifying workers of their fatal injury risks in a similar fashion that workers are informed of occupational illness and disease risks.

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Estimates of Lifetime Risk of Occupational Fatal Injury from Age-Specific Rates

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ABSTRACT

The lifetime risk of fatal workplace injury is a critical issue in the evaluation of occupational hazards. Recently, Fosbroke, Kisner, and Myers (1997) described a metric for working lifetime risk (WLTR) to determine the probability that a worker will die due to a work-related fatal injury in a year over a certain number of years of employment. This quantity was defined assuming that the annual rate of fatal injuries will be the same each year during employment. Recognizing the fact that annual fatal injury rates differ with the age of the worker along with other factors, modification of the definition of working lifetime risk is derived. We obtain the estimates of the lifetime risk using age-categorized annual fatality rates and derive an estimate of the standard error of the WLTR estimator and a confidence interval for the WLTR. We illustrate these calculations by estimating the lifetime risk for work-related fatal injuries for workers in four high-risk industries: agriculture-forestry-fishing, mining, construction, and transportation-public utilities. The estimates are based on employment data from the Bureau of Labor Statistics and an updated version of fatality data from the National Traumatic Occupational Fatalities surveillance system.

Key Words: confidence interval, delta method, risk assessment

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INTRODUCTION

The assessment of hazards associated with occupational fatal injuries is a broad public health concern with thousands of workers dying each year in the United States. A first step in the assessment of these hazards is to quantify risk or rates of fatal injuries. While rates are commonly employed in epidemiology studies, the lifetime probability of the occurrence of a certain event, *i.e.*, the *risk* of the event, is a more natural endpoint for risk estimation purposes. Lifetime risks of occupational fatal injury are of interest for comparison with the assessment of hazards associated with occupational disease or illness.

In an attempt to estimate the lifetime risk for workers in a specific industry, Fosbroke, Kisner, and Myers (1997) used the lifetime risk formula:

$$\mathrm{WLTR}_{\mathrm{F}} = \left[1-(1-R)^{y}\right] \times 1000 \tag{1.1}$$

where $R = P$ (a worker having a work-related fatal injury in a given year), $0 \le R \le 1$, and y is the number of years of exposure to work-related injury. Here, y was set at 45 years, which could represent an employment pattern where a worker starts work at age 20 and continues until retirement at age 65. This time period is consistent with work-life values used in many quantitative risk assessments for occupational illnesses (Stayner, 1992). The formula $\mathrm{WLTR}_{\mathrm{F}}$ expresses the risk as a rate over a hypothetical group of 1000 individuals who start working at age 20 and work to age 65 in the same industrial division. Fosbroke *et al.* (1997) estimated R in formula (1.1) from data from the National Institute for Occupational Safety and Health (NIOSH) National Traumatic Occupational Fatal (NTOF) surveillance system for the calendar year 1990 to 1991. The lifetime risk formula (1.1) assumes that the annual risk of fatal injury is constant for a working lifetime. However, the fatality rate R may vary with other covariates, such as number of years at work, age, calendar time, industry, and occupation. For example, as a worker gets more experienced at a job, he or she may experience less risk of a fatal injury; or the risk of fatal injury may increase with the age of the worker. The risk may depend on years of experience and age. Some injury prevention efforts, such as engineering controls, personal protective equipment, and training programs for new workers and new safety equipment may contribute to a further decline of the fatal injury rates. Thus, it may not be reasonable to assume that the annual rate is constant over a working lifetime. This will be illustrated with NTOF data in a subsequent section.

The purpose of this paper is to provide an estimate of the working lifetime risk that allows for the annual risk, R in (1.1), to change at different ages. We illustrate this with calculations that allow for different annual rates of fatal injury at different age intervals and illustrate how the working lifetime risk could be adjusted for a particular covariate. To measure the precision of the estimate, we obtain the standard error and confidence interval for the age-adjusted working lifetime risk estimator that we propose.

METHODS

Calculation of Working Lifetime Risk of Death

The working lifetime risk can be estimated by grouping the age scale into a number of categories $[a_k, a_{k+1})$. Five-year intervals are often used for this purpose. We assume that the working lifetime corresponds to employment from the age of 20 to 65. The survival times are grouped into intervals of five years $[a_k, a_{k+1})$ where $a_k = a_1 + 5(k-1)$ and $a_{k+1} = a_k + 5$, $k=1,2,\ldots,9$ with $a_1 = 20$. The annual risk of death (*i.e.*, the probability of a worker having a work-related fatal injury in a given year) is assumed to be constant over each categorized age interval $[a_k, a_{k+1})$. Let R_k, $0 \le R_k \le 1$, denote the annual risk of death associated with the age interval $[a_k, a_{k+1})$ and let λ_k denote the risk of death over a 5-year interval $[a_k, a_{k+1})$. Then, assuming independence of the occurrence of events between the years, we have

$$\lambda_k = 1 - \left(1 - R_k\right)^5 \tag{2.1}$$

$k = 1,2,\ldots,9$. The working lifetime risk (WLTR), the probability of dying over a working lifespan due to work-related injuries for workers in a specific industry (given survival to age $a_1 = 20$) is then

$$\text{WLTR} = 1 - \prod_{k=1}^{9} \left(1 - \lambda_k\right) = 1 - \prod_{k=1}^{9} \left(1 - R_k\right)^5 \tag{2.2}$$

assuming independence between the events occurring in two different age-intervals.

Interval Estimation of the Working Lifetime Risk

We now describe an interval estimation method to provide a measure of precision for the estimate of individual working lifetime risk. We demonstrate this by obtaining the standard error of the estimator WLTR in (2.2) and the endpoints of the confidence interval.

Let the random variable D_k denote the number of deaths in the kth 5-year age period, $I_k = [a_k, a_{k+1})$, $k = 1,2,\ldots,9$. We assume that the D_k are independently distributed with Poisson distribution with mean $\mu_k = N_k\lambda_k$. N_k denotes the number of workers alive at the start of the interval $[a_k, a_{k+1})$, and λ_k represents the risk of fatal injury during the 5-year age interval.

Let $\hat{R}_k$ denote the estimated annual risk of death during the years over the age interval $I_k = [a_k, a_{k+1})$. Note that each year in the interval I_k is assumed to have the same annual fatal injury rate. Suppose these estimates $\hat{R}_k$ are given for $k = 1,2,\ldots,9$. Then the estimates of 5-year risks $\hat{\lambda}_k$ are given by $\hat{\lambda}_k = 1 - (1 - \hat{R}_k)^5$. In this case, the estimator of the working lifetime risk ($\widehat{\text{WLTR}}$) is given by

$$1 - \prod_{k=1}^{9} \left(1 - \hat{\lambda}_k\right) = 1 - \prod_{k=1}^{9} \left(1 - \hat{R}_k\right)^5 \tag{2.3}$$

Under the above assumption, it can be shown that the maximum likelihood estimator for λ_k is

$$\lambda_k \text{ is } \hat{\lambda}_k = \frac{D_k}{N_k}$$

To determine the lower and upper bounds of the confidence interval for the WLTR estimator, we obtain approximate standard errors for the estimates of WLTR by applying the delta method (Bishop, Feinberg, and Holland, 1975). If the variance of $\hat{\lambda}_k$ is known, the method provides an approximation to the variance of the WLTR estimator, which is a function of the $\hat{\lambda}_k$, and therefore a function of $\hat{R}_k$ as in (2.3). We denote this function $W(\hat{\Lambda}) = W(\hat{\lambda}_1, \hat{\lambda}_2, \ldots, \hat{\lambda}_9)$. Then, the asymptotic distribution of the estimate of WLTR, $W(\hat{\Lambda}) = 1 - \Pi_{k=1}^{9}(1 - \hat{\lambda}_k)$, is given by

$$W(\hat{\Lambda}) \sim N\left(1 - \prod_{1}^{9}(1-\lambda_k),\ \prod_{k=1}^{9}(1-\lambda_k)^2 \sum_{k=1}^{9} \frac{\lambda_k}{N_k(1-\lambda_k)^2}\right) \quad (2.4)$$

Technical details for the delta method to obtain the asymptotic distribution of the WLTR in (2.4) are provided in the Appendix. The standard error of the estimate of WLTR, $s.e.(W(\hat{\Lambda}))$, is the square root of the estimated variance of $W(\hat{\Lambda})$. It follows that an approximate $100(1-\alpha)\%$ confidence interval for WLTR, $W(\hat{\Lambda})$, is

$$W(\hat{\Lambda}) \pm z_{\alpha/2} s.e.\left(W(\hat{\Lambda})\right) \quad (2.5)$$

where $z_{\alpha/2}$ represents the upper tail $\alpha/2$ critical value from a standard normal distribution.

RESULTS

In this section, we calculate the working lifetime risks for the four most hazardous industries in the United States. We estimate these values (as rates over every 1000 workers) by applying the formula derived in (2.2) based on age-specific annual fatality rates, along with a measure of precision. For comparison purposes, we also provide estimates of the previously studied working lifetime risk based on formula (1.1) for the four industries. We first describe the data that we use in this section.

The data from the NTOF surveillance system are combined with data on employment from the United States Bureau of Labor Statistics (BLS). This updated version of the data provides occupational fatal injury counts and the number of employed over the years from 1983 to 1992, respectively. The NTOF database is a death certificate-based census of occupational fatal injuries in the U.S. containing case data of deaths, including year of death, gender, race (white, black, other), age (collapsed into 9 intervals for our analysis), industry and occupation. The BLS employment data are based on unpublished data tabulated from the current population survey (U.S. Bureau of the Census, 1978) constructed in response to an interagency agreement between BLS and NIOSH. The fatal injury rates along with a complete description of the classification of industries and occupations are given in Bailer *et al* (1998). The identification of the four most hazardous industries is presented in Table 1. The table also includes annual fatal injury rates along with the fatality counts and number employed in 1992 for these four industries. The industry with the highest fatal injury rate was "mining" with 0.2114 deaths per 1000 workers, followed by "agriculture-forestry-fishing", "construction", and "transportation — public utilities."

The annual mortality rates across the four industries in 5-year age intervals from 20 to 65 based on 1992 data are given in Table 2. The third column of the table presents the age-specific annual fatality rates $\hat{R}_k$, which are calculated by

$$\hat{R}_k = \frac{\begin{pmatrix}\text{Number of fatal injuries occurring in 1992 among workers} \\ \text{in the } k\text{th age category}\end{pmatrix}}{\begin{pmatrix}\text{Number of workers in the } k\text{th age category} \\ \text{at the beginning of 1992}\end{pmatrix}}$$

Table 1. Annual fatality rates of the four most hazardous industries based on 1992 data.

Industry	Description (*e.g.*)	Annual fatal. rate $\hat{R}$ (/1000)	No. dead	Person-years
Agriculture, forestry, and fishing	Crops, livestock	0.1519	423	2,785,607
Mining	Metal, coal, oil and gas, sand and gravel	0.2114	136	643,253
Construction	General and heavy construction, special trade construction	0.1166	786	6,740,071
Transportation and public utilities	Railroad, cabs, trucking, water and air transportation	0.0928	743	8,008,784

This table indicates that the risk of fatal injury varies by age. For these industries, the rates generally decrease or are not changing from the age interval [25,30) through the interval [40,45). Then from age interval [45,50), the rates tend to increase with the highest fatal injury rates occurring in the oldest workers, in the interval [60,65). In the mining industry, the younger age groups [20,25) and [25,30) have the highest annual fatality rates of over 0.32 and 0.33 deaths, respectively, for every 1000 workers.

We now obtain the working lifetime risk for the industries by using the age-specific annual risk of death given in Table 2. We follow the procedures described in the previous section assuming that the annual risk is constant over each given 5-year age interval. The lifetime risk formula (2.3) estimates the average lifetime risk for workers in a given industry. We calculate WLTR based on age-specific fatality rates $\hat{R}_k$ from Table 2 as a rate over every 1000 workers, by the following formula

$$\mathrm{WLTR}_{\mathrm{A}} = \left[1 - \prod_{i=1}^{9} \left(1 - \hat{R}_k\right)^5\right] \times 1000 \tag{3.1}$$

The estimates $\mathrm{WLTR}_{\mathrm{A}}$ for the four industries are reported on the second column of Table 3. Among these four industries, the mining industry has the highest risk with a 95% confidence interval (9.08, 10.84) per 1000 workers while the transportation and public utility industry has the lowest risk (4.28, 4.62) per 1000 among the four industries. The last column of Table 3 provides working lifetime risks, which are calculated by using the formula $\mathrm{WLTR}_{\mathrm{F}}$ in (1.1) with the annual fatality rates given in Table 1. These estimates are not much far from the estimates by using age-specific annual rates. In fact, the estimates by $\mathrm{WLTR}_{\mathrm{F}}$ for the agriculture-forestry-fishing and mining industries are within the bounds of the 95% confidence intervals of the corresponding $\mathrm{WLTR}_{\mathrm{A}}$ values. The estimates for the other two industries are out of the ranges of the 95% confidence intervals for the estimates $\mathrm{WLTR}_{\mathrm{A}}$. In all four industries, the estimates $\mathrm{WLTR}_{\mathrm{A}}$ appear to be slightly higher than the estimates $\mathrm{WLTR}_{\mathrm{F}}$.

DISCUSSION AND CONCLUSION

The lifetime fatal injury risks $\mathrm{WLTR}_{\mathrm{A}}$ presented in Table 3 are similar to the estimates $\mathrm{WLTR}_{\mathrm{F}}$ based on formula (1.1), although the estimates $\mathrm{WLTR}_{\mathrm{A}}$ are always greater, ranging from 3 to 9 percent. Our proposed modification for estimating WLTR accommodates the possibility of age-related effects. We also illustrated how to determine a standard error and confidence interval for a WLTR estimator.

A projection of risk for a lifetime is clearly an extrapolation well beyond available data. We chose to base our risk extrapolations on the 1992 data since it was the most recent year observed. Given that 10 years of data were available for this analysis, we could have used regression estimates of the annual fatality

Table 2. Summary calculations for age-categorized annual risk for four high-risk industries based on 1992 data.

Industry	Age category	Annual fatal. rate $\hat{R}_k$ (/1000)	No. dead	No. employed
Agriculture, forestry, and fishing	20 to 24	0.1162	39	335,615
	25 to 29	0.1535	55	358,341
	30 to 34	0.1322	57	341,034
	35 to 39	0.1395	56	401545
	40 to 44	0.1591	52	326,926
	45 to 49	0.1018	27	265,354
	50 to 54	0.2125	49	230,566
	55 to 59	0.2158	48	222,449
	60 to 64	0.1871	40	213,377
Mining	20 to 24	0.3233	11	34,024
	25 to 29	0.3370	21	62,323
	30 to 34	0.2147	24	111,766
	35 to 39	0.1992	27	135,576
	40 to 44	0.1856	20	107,769
	45 to 49	0.1693	13	76,781
	50 to 54	0.1329	8	60,208
	55 to 59	0.2151	7	32,542
	60 to 64	0.2246	5	22,264
Construction	20 to 24	0.1086	76	700,123
	25 to 29	0.1176	119	1,012,109
	30 to 34	0.0934	115	1,231,214
	35 to 39	0.0997	111	1,113,819
	40 to 44	0.1160	105	905,213
	45 to 49	0.1393	89	639,058
	50 to 54	0.1397	72	515,492
	55 to 59	0.1339	56	389,036
	60 to 64	0.1838	43	234,007
Transportation and public utilities	20 to 24	0.0754	42	557,170
	25 to 29	0.0868	83	956,553
	30 to 34	0.0820	108	1,317,553
	35 to 39	0.0932	122	1,309,324
	40 to 44	0.0827	110	1,330,118
	45 to 49	0.0966	103	1,066,726
	50 to 54	0.1196	84	702,150
	55 to 59	0.0984	50	508,382
	60 to 64	0.1572	41	260,808

Table 3. Working lifetime risks $WLTR_A$ and WLTRF and the confidence intervals of $WLTR_A$ for the four industries based on 1992 data. All risks are per 1000 workers.

Industry	Lower bound of a 95% CI	$WLTR_A$[a]	Upper bound of a 95% CI	$WLTR_F$[b] (Diff. in %)
Agriculture, forestry, and fishing	6.75	7.06	7.37	6.81 (3.72%)
Mining	9.08	9.96	10.84	9.47 (5.17%)
Construction	5.49	5.69	5.90	5.23 (8.77%)
Transportation and public utilities	4.28	4.45	4.62	4.17 (6.79%)

[a] Estimated $WLTR_A$ with age-specific annual risk $\hat{R}_k$ (from Table 2) based on 1992 data.

[b] Estimated previously studied $WLTR_F$ (formula (1.1)) with annual risk $\hat{R}_k$ (from Table 1) based on 1992 data.

rates based on the data over the 10-year period from 1983 to 1992. However, a projection of a lifetime risk is an extrapolation that should be calculated with extreme caution; the potential problem surfaces if we attempt to extrapolate this prediction into a distant future that is far beyond the range of the data. We were concerned that using such a year-adjusted prediction of annual fatal injury risks would underestimate the true risk. Thus, to avoid the possibility of danger of projecting the rates to future calendar years, we suggest a conservative approach by using the most recent data available. While this may not be ideal, it may provide a conservative upper bound on the annual risk of occupational fatal injury.

In our calculation of $WLTR_A$, we assumed that the occupational fatal injury risk was constant over 5-year age intervals. The estimates $WLTR_A$ did not differ dramatically from the estimates $WLTR_F$. The greatest difference between the two estimates was observed for construction while the smallest difference was observed for agriculture-forestry-fishing. Examining Table 1 gives insight into why this is observed. Note that fatal injury risk generally increases with age for construction workers, while the risk by age category in workers in agriculture-forestry-fishing is more variable with the smallest risk observed in 45- to 49-year-old workers. The $WLTR_F$ essentially pools all of the data across all age categories which weights the data towards the age categories with a larger number of workers. In construction, the younger workers at lower risk of fatal injury are weighted more heavily in the calculation of $WLTR_F$ because most construction workers are younger than 44 years of age (68%). This leads to a difference from the estimate by $WLTR_A$ because of the increasing age-related trends in fatal injuries for the construction industry. In contrast, little difference between the two estimates would be expected for agriculture-forestry-fishing since the fatal injury risk does not vary systematically with age category.

As a final observation, the calculation of the WLTR of occupational injury might be incorporated in a comparative risk exercise. For example, the comparison of occupational fatal injuries and death due to lung cancer associated with exposure to some occupational carcinogen might be conducted. This calculation has an inherent shortcoming in that death due to lung cancer is generally a disease of older ages while occupational fatal injuries usually occur in younger workers (median age of death for workers in the NTOF data registry over the years 1983 through 1992 was 35 years). For a comparative risk calculation, other measures of injury have impact; for example, the years of potential life lost should be considered in addition to WLTR. In addition, lifetime risk assessments for illness are often adjusted for competing risks (*e.g.*, death due to heart disease is a competing risk for lung cancer death in smokers) which could be incorporated into a future extension of the methods we describe.

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APPENDIX

Asymptotic Distribution of WLTR

The asymptotic distribution of the estimates of WLTR given in (2.4) is obtained as follows:

1. For $D_k \sim Poisson(\mu_k = N_k\lambda_k)$ such that $Var(D_k) = N_k\lambda_k$ and

$$Var\left(\hat{\lambda}_k\right) = Var\left(\frac{1}{N_k} \times D_k\right) = \frac{1}{N_k^2} \times N_k\lambda_k = \frac{\lambda_k}{N_k}$$

To find the variance of $W(\hat{\Lambda})$, we apply the delta method twice — first to $\ln(1 - W(\hat{\Lambda}))$ and then to $\exp(\ln(1 - W(\hat{\Lambda})))$:

2. Let $\hat{\theta} = \ln\left(1 - W\left(\hat{\Lambda}\right)\right)$ and $g\left(\hat{\lambda}_k\right) = \ln\left(1 - \hat{\lambda}_k\right)$.

Then $\hat{\theta} = \sum_{k=1}^{9} \ln\left(1 - \hat{\lambda}_k\right) = \sum_{k=1}^{9} g\left(\hat{\lambda}_k\right)$.

Applying the delta method, we obtain the variance of $g(\hat{\lambda}_k)$ by

$$Var\left(g\left(\hat{\lambda}_k\right)\right) \approx Var\left(\hat{\lambda}_k\right)\left(g'\left(\lambda_k\right)\right)^2 = \frac{\lambda_k}{N_k}\left(\frac{1}{1-\lambda_k}\right)^2$$

Thus, the asymptotic distribution of $\hat{\theta}$ is given by

$$\hat{\theta} = \ln\left(1 - W\left(\hat{\Lambda}\right)\right) \sim N\left(\sum_{k=1}^{9} \ln\left(1-\lambda_k\right), \sum_{k=1}^{9} \frac{\lambda_k}{N_k\left(1-\lambda_k\right)^2}\right)$$

3. Since $W(\hat{\Lambda}) = 1 - \exp(\hat{\theta})$, by using the delta method again, we have

$$Var\left(W\left(\hat{\Lambda}\right)\right) \approx \left(\exp(\theta)\right)^2 Var\left(\hat{\theta}\right)$$

$$= \prod_{k=1}^{9} \left(1-\lambda_k\right)^2 \sum_{i=1}^{9} \frac{\lambda_k}{N_k\left(1-\lambda_k\right)^2}$$

$$\text{as} \left(\frac{d}{d\theta}\exp(\theta)\right)^2 = \left(\exp(\theta)\right)^2 = \left[\exp\left(\sum_{k=1}^{9} \ln\left(1-\lambda_k\right)\right)\right]^2 = \prod_{k=1}^{9} \left(1-\lambda_k\right)^2$$

Thus, the asymptotic distribution of WLTR, $W(\hat{\Lambda}) = 1 - \Pi_{k=1}^{9}(1 - \hat{\lambda}_k)$, is given by (2.4).

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Years of Potential Life Lost Due to Occupational Fatal Injury in the United States

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ABSTRACT

Fatal injury surveillance data coupled with life expectancy data may be used to assess the impact of occupational fatal injuries on years of potential life lost (YPLL).

We compare three definitions of YPLL and trends over time in YPLL. Two definitions determine YPLL as expected life lost to fixed life expectancies of 65 or 85 years. The third definition uses actuarial adjustments of life expectancy given survival to a given age stratified by gender and race. Fatalities from the National Traumatic Occupational Fatality (NTOF) database are used to illustrate the three definitions of YPLL.

The three YPLL measures were similar in magnitude and direction of the trend in YPLL over 1980–1992. Proper interpretation of these trends can only be made in conjunction with other measures (*e.g.*, rates). Almost all YPLL trends are declining, implying that over time fatal injuries are shifting to older workers. The exception is the increasing trend in YPLL for the retail trade industry, injury rates have also been increasing over time for this industry. Mining and construction have the highest YPLL among all industries. This analysis suggests efforts to prevent the occupational fatalities of younger workers should focus on the retail trade, mining, and construction industries.

Key Words: multiple regression, linear interpolation, actuarial adjustments

INTRODUCTION

William Haenszel (1950) suggested that chronic diseases associated with old age received a tremendous focus as perhaps the "most important public

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health problem of the day." However, he quickly noted that "there is plenty of room for effecting savings of potential years of life at younger ages, particularly from deaths due to accidents." It is with this observation in mind that we reflect on the analysis of years of potential life lost (YPLL).

The basic information for many occupational safety studies comes from injury surveillance data. The number of injuries and the corresponding number of workers employed are recorded for several levels of one or more predictor variables such as industry or occupation. Most studies of injuries are based on rates or counts of injury occurrence (see, *e.g.*, Stout *et al.*, 1996; Bailer *et al.*, 1998) or a measure trying to quantify the impact from each injury. While rates are an important outcome, they ignore an important aspect of occupational fatal injuries. Younger workers are often the victims of fatal injuries, resulting in greater YPLL than for most other causes of death (*e.g.*, cancer).

In this paper we present results from analyses using three different definitions of YPLL to determine which industries and occupations may need attention because of high YPLL or changes over time in YPLL. This paper also attempts to evaluate the impact of using different definitions of YPLL on the analyses. The first two definitions use fixed life expectancies of 65 and 85 years to determine YPLL. For these two definitions, the age at death for each person is subtracted from the fixed life expectancy to get YPLL. If the person dies at an age older than 65, the YPLL for the definition using the fixed life length of 65 years is set to zero years. Similarly, if the person dies past age 85, a YPLL of zero years is used for the definition using a life expectancy of 85 years. Fixed life expectancies of 65 and 85 years have been used by the U.S. Centers for Disease Control and Prevention (1997) for their computations of YPLL. A fixed life length for YPLL calculations has appeal in that a loss of life at a particular age is viewed as having equal impact regardless of any other characteristics of an individual. This fails to take into account the clear pattern of differences in expected life length between women and men and across different racial/ethnic groups. The third YPLL definition uses actuarial adjustments on life expectancy to determine YPLL to address this concern. Adjustments for age at death, gender, and race from Hahn and Eberhardt (1995) are used. We apply these three definitions to explore the average YPLL across different worker and workplace characteristics and trends over the years 1980 to 1992 in YPLL due to occupational fatal injuries.

METHODS

Data

The occupational fatal injury data considered in this analysis comes from the National Institute for Occupational Safety and Health's (NIOSH) National Traumatic Occupational Fatal (NTOF) injury data set. The NTOF database is a death certificate-based registry of occupational fatal injuries in the U.S. containing information about each fatality on age, gender, race, industry, and occupation within industry. A more detailed description of these variables and their codes can be found in NIOSH (1993).

Years of Potential Life Lost Calculations

The calculation of YPLL using a fixed life expectancy is straightforward and is computed as the life expectancy minus the age at death. We will compare fixed life expectancies of 65 and 85 years. Constructing YPLL from fixed time points like age 65 is useful because it can be used for comparisons with other countries that have different life expectancies or where actuarially adjusted life expectancy is not available. Age 85 is useful to see how using a longer fixed life expectancy affects YPLL or trends in YPLL over time. For example, suppose a worker dies at age 27 and their life expectancy is 65 years. Their YPLL would be 65 – 27 = 38 years. As an aside, using a fixed life expectancy of 65 years might be better described as years of working life lost. Similarly, if their life expectancy is 85 years then their YPLL would be 85 – 27 = 58 years. The age at death is greater than 65 years for some workers and others die at an age greater than 85 years: for these workers the YPLL is set to zero when they die at an age greater than the life expectancy being used. For example, if a worker dies at the age of 72 due to an occupational fatality and life expectancy is assumed to be 65 years then their YPLL would be zero years; however if we assume a life expectancy of 85 that same person would have a YPLL of 85 – 72 = 13 years. For workers who die after age 85, their YPLL is zero years for both fixed life expectancies.

YPLL can be calculated using actuarial adjustments for survival until time of death, gender, and race. We calculate the YPLL based upon the life expectancy data given in the "*Adjusted for undercount and misclassification*" section of Table 2 in Hahn and Eberhardt (1995) which is reproduced, in part, in Table 1. This table indicates that women have higher predicted years of life remaining than men across almost all races and attained ages. Table 1 also shows that Asians generally live longer than blacks, Native Americans, and whites. The prediction of YPLL for an individual dying at an age in between

Table 1. Predicted years of life remaining for different gender/racial groups.[a]

Age	Black		Native American		Asian/Pacific Islander		White	
(years)	Male	Female	Male	Female	Male	Female	Male	Female
1	65.5	73.5	71.3	78.7	81.5	85.3	72.5	78.9
25	43.1	50.1	49.4	55.7	58.7	62.0	49.5	55.5
45	26.7	31.9	32.5	37.2	39.7	42.5	31.2	36.3
65	13.7	17.7	17.2	20.8	22.6	24.5	15.4	19.1
≥85	6.4	7.5	6.8	8.3	11.4	10.0	6.0	6.9

[a] Extracted from Table 2 in Hahn and Eberhardt (1995).

Table 2. Mean age at death and mean YPLL due to occupational fatalities using different definitions of YPLL for different predictor variables.

Factor	Level	Age at death	$YPLL_{65}$[a]	$YPLL_{85}$[a]	$YPLL_{AA}$[a]
Year	1980	40.44	25.05	44.57	35.97
	1981	40.16	25.31	44.85	36.28
	1982	40.70	24.80	44.31	35.83
	1983	40.92	24.57	44.09	35.62
	1984	40.62	24.87	44.39	35.93
	1985	40.90	24.56	44.10	35.62
	1986	41.07	24.46	43.94	35.49
	1987	41.77	23.78	43.23	34.84
	1988	41.61	23.95	43.40	35.05
	1989	41.93	23.57	43.08	34.70
	1990	41.91	23.64	43.10	34.83
	1991	42.33	23.18	42.67	34.45
	1992	42.65	22.91	42.35	34.22
Gender	Male	41.36	24.16	43.65	34.96
	Female	39.48	25.97	45.53	41.74
Race	White	41.35	24.19	43.65	35.63
	Black	40.77	24.53	44.23	31.40
	Native American	37.44	27.82	47.60	38.51
	Asian	40.27	24.97	44.73	44.88

Industry	Ag, for, and fishing	47.81	19.04	37.22	30.38
	Mining	36.24	28.92	48.76	39.48
	Construction	39.03	26.21	45.98	36.86
	Manufacturing	41.21	24.14	43.80	35.02
	Trans and pub utilities	40.26	24.92	44.74	35.76
	Wholesale trade	40.26	25.12	44.74	36.11
	Retail trade	41.97	23.62	43.03	35.81
	Fin, ins and real estate	45.01	20.68	40.00	33.03
	Services	41.62	23.89	43.38	35.48
	Public Admin	39.58	25.65	45.43	36.43
Occupation	Exec, admin, and manag	45.44	20.12	39.56	32.18
	Prof specialty	43.00	22.51	42.00	34.55
	Tech and related support	37.69	27.40	47.31	38.44
	Sales	44.60	21.15	40.41	33.63
	Admin support incl clerical	41.09	24.46	43.91	37.04
	Service	39.80	25.56	45.20	36.63
	Farm, for, and fishing	47.48	19.28	37.56	30.49
	Prec prod, craft and repair	39.73	25.55	45.27	36.40
	Mach op/assem/inspect	39.69	25.61	45.32	36.42
	Transp/material moving	40.22	24.94	44.79	35.75
	Handlers/helpers/laborers	35.78	29.42	49.22	39.36

[a] YPLL65, YPLL85, and YPLLAA use life expectancies of 65 years, 85 years, and actuarially adjusted, respectively.

category endpoints in Table 1 is determined by linear interpolation. The predicted YPLL for an individual dying at age x (<85 years), which is in an interval bracketed by age categories in Table 1, say (t_{p-1}, t_p), is

$$YPLL = YPLL_{p-1} + \left(x - t_{p-1}\right)\left(\frac{YPLL_p - YPLL_{p-1}}{t_p - t_{p-1}}\right)$$

While the predicted YPLL for an individual dying at age x (≥85 years) is calculated as

$$YPLL = YPLL_{85} + \left(x - 85\right)\left(\frac{YPLL_{85} - YPLL_{65}}{85 - 65}\right)$$

As an example, suppose an Asian female worker dies at age 50. Using the data from Table 1, her calculated YPLL is

$$42.5 + \left(50 - 45\right)\left(\frac{24.5 - 42.5}{65 - 45}\right) = 42.5 + 5\left(\frac{-18}{20}\right) = 42.5 - 4.5 = 38.0$$

Statistical Analyses

Multiple regression models (Neter, Wasserman, and Kutner, 1990) are used to examine the relationship between YPLL and calendar year and worker/workplace characteristics. Gender and race worker characteristics, and occupation and industry workplace characteristics were considered in the analysis. As an example, the multiple regression model in which all predictor variables enter the model additively can be written as:

$$\begin{aligned} YPLL_i = {} & \beta_0 + \beta_1\, year_i + \beta_2 year_i + \beta_2 I(female_i) \\ & + \beta_3 I(black_i) + \beta_4 I(Native\ American_i) + \beta_5 I(Asian_i) \\ & + \sum_j \alpha_j I(industry_i = j) + \sum_k \phi_k I(occupation_i = k) + \varepsilon_i \end{aligned} \quad \text{(Model 1)}$$

where "i" is the index associated with a particular individuals fatal injury; "j" is the index for the different industries; "k" is the index for the different occupations; the β's, α's, and ϕ's are regression coefficients associated with the various predictor variables; and ε_i is assumed to be an independent normally distributed quantity. The predictor variable year is continuous and enters the model as one variable. We chose to model the year of death as a continuous predictor because decreases in mean YPLL over the years 1980 to 1992 are essentially constant from year to year regardless of the definition of YPLL used (see Table 2). For example, if $\beta_1 < 0$, this implies that predicted mean YPLL is decreasing with calendar time suggesting that fatal injuries tend to be shifting towards older workers. The categorical predictor variables (race, gender, industry, and occupation) enter the model as a series of indicator variables. In particular, if the categorical predictor variable has n levels, then that predictor requires $n-1$ indicator variables in the model (see Neter, Wasserman, and Kutner 1990). For example, the indicator variable $I(\text{female}_i) = 1$ if the i^{th} worker is female and $I(\text{female}_i) = 0$ if the i^{th} worker is male. The reference groups for gender, race, industry, and occupation are male, white, agriculture-forestry-fishing, and executive-administration-manager respectfully. We will also look at trends in YPLL over the years 1980 to 1992 for each level of gender, race, industry, and occupation using the three different definitions of YPLL discussed in the Introduction and Methods sections.

RESULTS

The YPLL methods and statistical models described in the Methods section are illustrated with data from the NTOF database. A total of 67,218 traumatic occupational fatalities were used in this analysis. Traumatic occupational fatalities occurring after age 65 total 4529 with 128 of those occurring after age 85.

Table 2 illustrates the mean age at death and the mean YPLL for each definition at different levels of calendar year, gender, race, industry, and occupation. There is a very slight decrease in mean YPLL over time for each of the three definitions. The mean YPLL for females is higher than males, regardless of how YPLL is defined. While either fixed life length YPLL definition suggests women experience approximately 1.8 years less life than men due to fatal injuries, the actuarially adjusted YPLL suggests a more dramatic effect of almost 7 fewer years. This difference between definitions illustrates how discrepancies can occur between actuarially adjusting the life expectancy for survival to some age, gender, and race versus using a fixed life expectancy. The pattern for the actuarially adjusted mean YPLL within race is similar to the life expectancies seen in Table 1. The mean YPLL for Asians is largest, the mean YPLL for Native Americans is second largest, the mean YPLL for whites is second smallest, and the mean YPLL for blacks is the smallest. In the fixed life expectancy definitions of YPLL, the highest YPLL is among Native Americans which indicates Native Americans are dying from occupational accidents at relatively younger ages than blacks, whites, and Asians. The mean YPLL is highest for the mining industry and second highest for the construction industry. The mean YPLL for the construction industry is about three years less than that of mining. Implicit in such a statement is that relatively younger workers tend to be dying in mining as compared to construction. The lowest YPLL among the remaining industries were for agriculture/forestry/fishing and financial/insurance/real estate. The highest mean YPLL among all occupations occurs in handlers/helpers/laborers and technical/related support regardless of the YPLL definition used.

Table 3 shows the parameter estimates and p-values for the trend in YPLL between 1980 and 1992 for different levels of factors with no adjustments for the other factors. In essence, a trend in YPLL indicates some change in the pattern in the age characteristics of workers dying in occupational fatal injuries. A decreasing trend suggests a shift in the average age at death towards older workers while an increasing trend suggests a shift toward younger workers dying in occupational accidents over the years 1980 to 1992. For example, the model

$$YPLL_i = \beta_0 + \beta_1 year_i + \varepsilon_i \qquad \text{(Model 2)}$$

is fit separately to males and females in order to assess differences in trends between men and women. Table 3 summarizes the parameter estimates of β_1 along with their p-values for different definitions of YPLL. Model 2 was also fit separately to each category of race, industry, and occupation to evaluate the trend differences in YPLL for different levels of those predictors. The mean YPLL for both men and women declined significantly regardless of YPLL definition with males decreasing slightly faster than females. In other words, deaths among males are shifting towards older workers faster than fatalities among women dying in occupational fatal injuries. The mean YPLL for whites and blacks have significantly decreasing trends with the trend for whites decreasing at twice the rate of blacks. There are significant declines in the trend of mean YPLL between 1980 and 1992 for mining, construction, manufacturing, transportation/public utilities, wholesale trade, services, and public administration industries. However, the trend in mean YPLL for the retail trade industry has increased significantly. A corresponding increase in the trend in rates of occupational fatalities was also seen for retail trade (Bailer *et al.*, 1998). Thus, not only are fatalities in retail trade occurring in relatively younger workers, the overall rate of such events occurring is increasing. This may be due to an influx of a large number of inexperienced young workers in the retail trade industry. Significant decreasing trends in mean YPLL are seen for the occupations of professional specialty, technical/related support, precision production/craft/repair, machine operator/assembler/inspection, transportation/material moving, and handlers/helpers/laborers with the highest reduction appearing in technical/related support. The definition of YPLL has a negligible effect on the direction (positive or negative) or magnitude (absolute value) of trends in YPLL.

Table 4 shows parameter estimates and p-values for the trend in YPLL between 1980 and 1992 for different levels of factors with adjustments for all other factors. A model similar to Model 2 was used with the modification that all other factors were also included in the model. For example, a model with an intercept, calendar year, race, industry, and occupation was fit separately to males and females. Similar models were fit separately to the different levels of

Table 3. Trend estimates (p-value) from 1980 to 1992 with no adjustments for other factors using different definitions of YPLL.

Factor	Level	Trend$_{65}$[a]	Trend$_{85}$[a]	Trend$_{AA}$[a]
Gender	Male	–0.19 (.0001)	–0.20 (.0001)	–0.17 (.0001)
	Female	–0.12 (.0432)	–0.11 (.0824)	–0.11 (.0451)
Race	White	–0.20 (.0001)	–0.21 (.0001)	–0.18 (.0001)
	Black	–0.10 (.0149)	–0.11 (.0108)	–0.08 (.0163)
	Native American	–0.02 (.9290)	0.03 (.8770)	–0.00 (.9967)
	Asian	–0.04 (.6432)	–0.04 (.7224)	–0.05 (.6027)
Industry	Ag, for, and fishing	–0.08 (.0869)	–0.09 (.0986)	–0.07 (.1108)
	Mining	–0.60 (.0001)	–0.61 (.0001)	–0.55 (.0001)
	Construction	–0.16 (.0001)	–0.17 (.0001)	–0.15 (.0001)
	Manufacturing	–0.19 (.0001)	–0.20 (.0001)	–0.16 (.0001)
	Trans and pub utilities	–0.27 (.0001)	–0.28 (.0001)	–0.25 (.0001)
	Wholesale trade	–0.35 (.0001)	–0.37 (.0001)	–0.35 (.0001)
	Retail trade	0.16 (.0009)	0.18 (.0007)	0.17 (.0001)
	Fin, ins and real estate	–0.20 (.0817)	–0.20 (.1203)	–0.17 (.1082)
	Services	–0.09 (.0366)	–0.08 (.0683)	–0.08 (.0423)
	Public Admin	–0.28 (.0001)	–0.29 (.0001)	–0.23 (.0001)

Table 3. Trend estimates (p-value) from 1980 to 1992 with no adjustments for other factors using different definitions of YPLL. (continued)

Factor	Level	$Trend_{65}$[a]	$Trend_{85}$[a]	$Trend_{AA}$[a]
Occupation	Exec, admin, and manag	–0.06 (.2501)	–0.06 (.2559)	–0.03 (.5457)
	Prof specialty	–0.23 (.0005)	–0.24 (.0007)	–0.19 (.0019)
	Tech and related support	–0.35 (.0001)	–0.36 (.0001)	–0.32 (.0001)
	Sales	–0.03 (.6442)	–0.03 (.5976)	0.01 (.8787)
	Admin support incl clerical	–0.06 (.5468)	–0.05 (.6460)	–0.06 (.5275)
	Service	–0.09 (.0713)	–0.10 (.0690)	–0.07 (.1073)
	Farm, for, and fishing	–0.01 (.8172)	–0.00 (.9695)	–0.01 (.8802)
	Prec prod, craft and repair	–0.20 (.0001)	–0.21 (.0001)	–0.19 (.0001)
	Mach op/assem/inspect	–0.22 (.0008)	–0.22 (.0009)	–0.20 (.0007)
	Transp/material moving	–0.26 (.0001)	–0.27 (.0001)	–0.25 (.0001)
	Handlers/helpers/laborers	–0.24 (.0001)	–0.24 (.0001)	–0.19 (.0001)

[a] $Trend_{65}$, $Trend_{85}$, and $Trend_{AA}$ use life expectancies of 65 years, 85 years, and actuarially adjusted, respectively.

Table 4. **Trend estimates (p-value) from 1980 to 1992 with adjustments for all other factors using different definitions of YPLL.**

Factor	Level	$Trend_{65}$[a]	$Trend_{85}$[a]	$Trend_{AA}$[a]
Gender	Male	–0.17 (.0001)	–0.17 (.0001)	–0.15 (.0001)
	Female	–0.11 (.0657)	–0.10 (.1259)	–0.10 (.0685)
Race	White	–0.18 (.0001)	–0.18 (.0001)	–0.16 (.0001)
	Black	–0.10 (.0174)	–0.11 (.0121)	–0.09 (.0068)
	Native American	–0.06 (.7479)	–0.01 (.9683)	–0.01 (.9503)
	Asian	–0.02 (.8148)	–0.01 (.9019)	–0.03 (.7470)
Industry	Ag, for, and fishing	–0.04 (.4078)	–0.04 (.4570)	–0.04 (.3481)
	Mining	–0.58 (.0001)	–0.59 (.0001)	–0.52 (.0001)
	Construction	–0.16 (.0001)	–0.17 (.0001)	–0.15 (.0001)
	Manufacturing	–0.19 (.0001)	–0.20 (.0001)	–0.17 (.0001)
	Trans and pub utilities	–0.26 (.0001)	–0.27 (.0001)	–0.24 (.0001)
	Wholesale trade	–0.32 (.0001)	–0.34 (.0001)	–0.29 (.0001)
	Retail trade	0.16 (.0006)	0.17 (.0006)	0.14 (.0008)
	Fin, ins and real estate	–0.20 (.0764)	–0.19 (.1226)	–0.18 (.0788)
	Services	–0.10 (.0191)	–0.09 (.0392)	–0.09 (.0160)
	Public Admin	–0.29 (.0001)	–0.29 (.0001)	–0.26 (.0001)

Table 4. Trend estimates (p-value) from 1980 to 1992 with adjustments for all other factors using different definitions of YPLL. (continued)

Factor	Level	$Trend_{65}$[a]	$Trend_{85}$[a]	$Trend_{AA}$[a]
Occupation	Exec, admin, and manag	–0.08 (.0953)	–0.09 (.1042)	–0.08 (.0869)
	Prof specialty	–0.24 (.0003)	–0.25 (.0005)	–0.21 (.0003)
	Tech and related support	–0.35 (.0001)	–0.36 (.0001)	–0.32 (.0001)
	Sales	–0.04 (.4331)	–0.05 (.3793)	–0.04 (.3708)
	Admin support incl clerical	–0.07 (.5184)	–0.06 (.6079)	–0.06 (.5667)
	Service	–0.09 (.0883)	–0.09 (.0901)	–0.08 (.0617)
	Farm, for, and fishing	–0.03 (.5093)	–0.03 (.5961)	–0.03 (.4741)
	Prec prod, craft and repair	–0.17 (.0001)	–0.17 (.0001)	–0.15 (.0001)
	Mach op/assem/inspect	–0.19 (.0037)	–0.19 (.0042)	–0.17 (.0025)
	Transp/material moving	–0.25 (.0001)	–0.26 (.0001)	–0.23 (.0001)
	Handlers/helpers/laborers	–0.27 (.0001)	–0.27 (.0001)	–0.24 (.0001)

[a] $Trend_{65}$, $Trend_{85}$, and $Trend_{AA}$ use life expectancies of 65 years, 85 years, and actuarially adjusted respectively.

race, industry, and occupation. The results are similar to what was seen in Table 3 when no adjustments for other factors were made. The trend in YPLL from 1980 to 1992 for males and females has been decreasing with the YPLL for males decreasing slightly faster. The trend is significant for males in all definitions but is borderline significant for females depending on which YPLL definition is used. All races show a decreasing trend in mean YPLL with whites decreasing almost twice as fast as blacks. However, the trends in YPLL for Native Americans and Asians are not significant for any definition of YPLL suggesting that the age of workers dying in these groups has been stable over the years 1980 to 1992. The trends in YPLL for the mining, construction, manufacturing, transportation/public utilities, wholesale trade, services, and public administration industries are significantly declining regardless of definition. Trends in mean YPLL for the agriculture/forestry/fishing and finance/insurance/real estate industries are decreasing, but the trends are not significant.

DISCUSSION

YPLL is a useful measure of the impact of traumatic occupational fatalities. It measures mortality with large values suggesting the death of younger workers. Many other endpoints such as healthy life-years (Hyder AA, Rotllant G, and Morrow RH 1998), disability adjusted life-years (Murray CJL 1994), or simple mortality rates can also provide a measure of the magnitude of each fatal injury. We recognize that YPLL may lack information that occurs in other measures that try to measure the impact of traumatic occupational fatalities. These alternative measures may be better than YPLL at assessing some characteristics of unintentional fatal injuries at work. One advantage of using YPLL, especially the fixed life expectancy definition, is ease of computation. A disadvantage of YPLL is that it lacks information on both the size of the workforce and the rate of fatal injury within each unique category of possible predictors such as gender, race, industry, and occupation. An ideal measure would integrate the size of the workforce, the rate of fatal injury, and some measure indicating the impact of each fatality.

The NTOF database from NIOSH is an ideal data source because we are interested in modeling individual occupational fatalities. Another potential source of data is the Census of Fatal Occupational Injuries (CFOI), a Federal-State cooperative program sponsored by the Bureau of Labor Statistics (1997). The CFOI contains more deaths each year than the NTOF database because it draws data from several sources, however, it wasn't implemented in all 50 states and the District of Columbia until 1992. If we had data from the CFOI for the years 1980 to 1992, the additional deaths probably wouldn't affect the results too much since we are essentially modeling the mean YPLL and the trend of those means. The CFOI data, starting in 1992, could be used to validate the trends in YPLL from 1980 to 1992 seen with the NTOF data.

That trends in the YPLL due to occupational fatal injuries are generally decreasing begs a few questions about the interpretation of these findings. Are the mean values of YPLL decreasing because the age of the worker population is simply increasing or is this due to a true shift in the distribution of age at the time of death? Even if these trends do represent a true shift in the age distribution of the deaths, should a shift in mortality from younger to older workers be viewed as a success when our goal is clearly to protect all workers? Proper interpretation of these trends can only be made in conjunction with other measures of injuries such as trends in the fatality rates. The fact that both YPLL and fatality rates are declining for almost all of these industries and occupations (Bailer *et al.*, 1998) does suggest that current programs are having an effect on reducing the impact of fatal injuries in the workplace. The fact that trends in both YPLL and fatality rates are increasing in the retail trade industry raises concerns that further attention needs to be focused on reducing fatal injuries in this industry sector.

The highest mean YPLL occurs in the mining and construction industries but these industries also show significant decreases in YPLL over time. Mining has the largest decline in YPLL over time of all industries. These two industries also have the highest fatal injury rates, which are declining over time (Bailer *et al.*, 1998). Although improvements have been made in reducing mean YPLL and fatal injury rates, efforts should continue to be focused toward mining and construction industry workers to prevent the occupational fatalities of these workers. The mean YPLL in retail trade industry is similar to other industries but significantly increases over time. This may be the result of the large number of young workers in retail trade. The increasing trend in rates of occupational deaths for retail trade (Bailer *et al.*, 1998) supports an argument that efforts should be centered on the retail trade industry to determine why occupational fatalities are shifting toward younger workers at increasing incidence rates.

The three different definitions of YPLL had little effect on the analysis of trends in the mean YPLL over the years 1980 to 1992. In contrast, the alternate definitions yield different means and we believe that the actuarially adjusted definition of YPLL is the preferred construction for looking at the average YPLL or the total YPLL. While using an actuarially adjusted YPLL may lessen the harm to groups with lower life expectancies, the use of a fixed life expectancy reduces the harm to groups with higher life expectancies. First, the actuarially adjusted YPLL, say $YPLL_{AA}$, utilizes all of the observed fatalities. The YPLL employing age lost to a fixed age, say $YPLL_F$, assigns all deaths in workers who are older than the fixed calculation age a YPLL of zero. This suggests that some loss of information or some potential bias might be introduced when using the $YPLL_F$ in contrast to the $YPLL_{AA}$. Secondly, the choice of the fixed age for $YPLL_F$ calculation is arbitrary. Finally, the actuarially adjusted YPLL is based upon current expectations of years of life remaining. There is a precedent for such calculations — obviously, stratified lifetable calculations are used by insurance companies in setting life and health insurance rates. Even though women generally live longer than men, we are not suggesting that an occupational fatality occurring to a 35-year-old woman is somehow more tragic than an occupational fatality to a 35-year-old man. Any loss of life is tragic. We are suggesting that the definition of YPLL to reflect current population lifetables does validly reflect the magnitude of life lost in a manner that is less arbitrary than evaluating loss of life to a fixed age. As an aside, the $YPLL_{AA}$ can be updated to reflect changes in the population lifetable when such information is available. Thus, by using appropriate actuarial adjustments, we believe that we are more accurately reflecting the true potential years of life lost.

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Identifying Populations at High Risk for Occupational Back Injury with Neutral Networks

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ABSTRACT

For this study a simulation is conducted to investigate the accuracy of neural networks and logistic regression in identifying populations at high risk for occupational back injury. In contrast to most standard regression techniques, neural networks do not rely on linearity or explicitly specifying the nature of the association. Because the underlying relationships between work exposures, personal risk factors, and injury are often not well defined, neural networks may prove useful for injury risk assessment. Accuracy was assessed by comparing the injury status to the predicted level of risk in each worker. In simulations of a non-linear association, workers (used in the training data) were correctly classified 85% of the time with neural networks, 74% of the time with the main effects logistic model, and 79% of the time with the fully-specified logistic model. Using the test data, however, workers were correctly classified 67% of the time with neural networks, and 71% and 69% of the time with the main effects and fully-specified logistic models, respectively. Simulations of a null association indicated that neural networks may be more likely to overfit random associations. These findings provide a valuable guide concerning statistical methodology for identifying high-risk worker populations.

Key Words: classification, logistic regression, simulation study.

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INTRODUCTION

An important aspect of occupational injury research is the assessment of an individual worker's risk for injury (Courtney *et al.*, 1997). By classifying each worker into low- or high-risk categories we can identify which segment of the population is at high risk for occupational back injury. Identification of a high-risk population allows researchers to better focus and evaluate interventions or treatments. Classification results from neural networks are compared to classification results from logistic regression to assess each methods' accuracy in identifying high-risk populations.

The motivation for utilizing neural networks in this setting is to address the analysis of non-linear associations in the data. The neural network model does not make any assumptions about the nature of an association between the outcome and predictors (Stern, 1996). If the exact nature of these relationships are known then the probability of injury can be explicitly modeled with logistic regression (Hosmer and Lemeshow, 1989) using appropriate categories or transformations. Otherwise, if we cannot explicitly specify the general nature of the non-linear association (such as quadratic or cubic), extensive exploratory analysis becomes necessary. Due to practical limitations in cases where a very small percentage of the population is injured, adequate data may not exist for thoroughly investigating the underlying structure of the data. Neural networks offer another approach to analyzing non-linear associations when we cannot adequately define the nature of the associations based on prior knowledge (Ripley, 1993). Other methods, such as generalized additive models, offer additional approaches which may be more easily interpreted. Comparisons between neural nets and such methods are not explored in this study. Methods for interpreting neural network parameters are less developed with neural networks than with standard methods (Lippmann and Shahian, 1997), thus providing further motivation to avoid using neural nets for statistical inference/estimation if the underlying data structure can be adequately described. Very few publications have thoroughly researched parameter interpretation with neural nets.

Neural networks should only be thought of as an exploratory technique in that the nature of the association between predictors and outcome is implicitly determined. In contrast to standard regression methods, further knowledge about this relationship, other than which variables to include in the model, is not required (or even useful) for neural network analysis. The network transforms the data to find the optimal classification of (for instance) cases and controls. Significance testing and estimation of summary measures is possible, although more difficult, with neural networks (Lippmann and Shahian, 1997; Landsittel, 1997). Neural networks are typically implemented for prediction, especially when the underlying structure of the data is very complex and/or unknown.

Numerous statistical techniques have been implemented for the purposes of classification, or identification of high-risk populations. Logistic regression, which uses maximum likelihood methods to fit the data to a linear function (in the logit scale) of the predictors and interactions, often serves as the standard statistical method for classification (Tu and Guerriere, 1993; Ripley, 1994; Tu, 1996, Duh *et al.*, 1998b). Other methods, such as probit analysis, discriminant analysis (Anderson, 1984) and classification and regression trees (Breiman, 1984), utilize different criteria or different assumptions to determine the optimal classification model. Modern regression techniques, such as projection pursuit regression (Friedman, 1987; Jones and Sibson, 1987) and multivariate adaptive regression splines (Friedman, 1991), have also been implemented for classification. Past research has indicated that such techniques may improve classification results in clinical settings, although results are not conclusive (Tu and Guerriere, 1993; Ripley, 1993; Ripley, 1994; Yarnold, 1995; Tu, 1996; and Duh *et al.*, 1998b). Analysis of a dichotomous outcome has been the most common application of neural nets in the statistical literature. Other applications, such as survival analysis (Faraggi and Simon, 1995), have been addressed elsewhere but are not considered in this study. Although appropriate for this study, methods for analysis of rates (with techniques comparable to Poisson regression) have not been developed for neural networks.

The field of occupational injury provides an excellent setting to examine the utility of neural networks for analyzing complex non-linear associations. Numerous measurements related to job activities and work exposures are often considered in assessing an individual's risk for injury (Hagberg *et al.*, 1997). Individual, physical workload, and organizational indices, as well as other occupational variables, have been linked to occupational injury (Burdorf *et al.*, 1997; Punnett, 1991). However, the nature of their association with injury is often difficult to define (Burdorf, 1992; Burdorf *et al.*, 1997; Hagberg *et al.*, 1997).

The goal of this study is to investigate neural networks specifically for identification of populations at high risk for occupational back injury. Due to the computational demands of the iterative procedures required for neural network analysis, the simulations are limited in terms of varying the simulation parameters, such as sample size, number of variables, and the network structure. Variations in these parameters could lead to different results and conclusions. Despite this restriction, this study makes a unique contribution to the neural net literature, as neural nets had not been previously applied to risk assessment in the field of occupational injury. In addition, most of the past publications, which utilized neural nets for prediction, were also limited in terms of varying network parameters (Lette *et al.*, 1994; Ripley, 1994; Loannidis *et al;* 1998) and utilized only a single data set to make conclusions (Tu and Guerriere, 1993; Koutsoukos *et al;* 1994; Lette, *et al.*, 1994; Lippman and Shahian, 1997; Duh *et al.*, 1998b; Loannidis *et al.*, 1998).

Distributions and associations were selected based on the appropriate literature to resemble (as closely as possible) true associations between injury and selected risk factors. As described in the methods, the specified covariates were chosen since their affect on the probability of back injury has been established but the exact nature of the (probably non-linear) associations is unclear, thus motivating the implementation of neural networks. For this study, simulations only address the question of whether neural nets can better identify populations at high risk for back injury when associations are not linear in a logit scale. These associations were limited to relationships considered realistic for ergonomic assessment measures and back injury, and therefore may not be the best examples of non-linearity appropriate for neural network analysis. Negative results should therefore not necessarily discourage use of neural models, but rather lead to further investigation of more optimal applications.

NEURAL NETWORK STRUCTURE

The basic unit of a neural network model is the semi-linear unit (Figure 1), which is similar to the logistic regression model. Define **s** as the network's inputs, which is simply the data for purposes of this study. The output, or response, of the semi-linear unit is determined by calculating the logistic function (Equation 1) of **x**, which is the vector product of the inputs and corresponding weights, **w**, so that $\mathbf{x} = \mathbf{w} \cdot \mathbf{s}$ (Levine, 1991).

$$f(\mathbf{x}) = 1/\left(1+\exp\left(-\mathbf{x}\right)\right) \tag{1}$$

One distinction between the logistic regression model and the semi-linear unit is that the logistic function, in a semi-linear unit, is used to approximate the threshold function (*i.e.,* whether the neuron fires a signal). In logistic regression, the outcome is predicted as a linear function of the data in the logit scale (Hosmer and Lemeshow, 1989). Although the logit function is most commonly used, other functions, such as the probit function may be utilized. Ramifications of using a different function are not clear. The predicted prob-

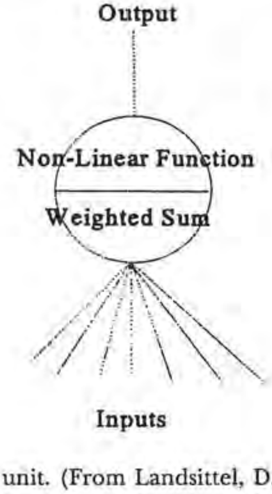

Figure 1. The semi-linear unit. (From Landsittel, D.P., Gardner, L.I., and Arena, V.C.)

ability from a neural net is not necessarily a linear function of the predictors and/or interactions (in any scale).

Other differences between the neural network model and logistic regression relate to the organization of semi-linear units into layers of the network. The neural network model is formed by connecting layers of semi-linear units, so that the outputs of units in one layer are used as inputs to the next layer (Levine, 1991). The initial layer of the network is the raw data and the layers between the first and last layers of the network are called hidden layers (since their outputs are hidden to the user). The final layer determines the response of the network, which in our case is the predicted probability of injury. In this study we utilize a network with one hidden layer and ten hidden units (Figure 2).

The purpose of utilizing hidden units is to transform the data into linearly separable groups (Levine, 1991). The output of the network can then be determined by classifying the data based on the weighted sum of the outputs of the hidden units. Interactions between variables and associations with the outcome are therefore implicitly determined by the network. It is unclear which types of associations in clinical or occupational settings are best classified by neural networks. The major trade-off between the two methods is that neural networks offer the flexibility of fitting non-linear associations without specifying the exact nature of the relationship, while logistic regression models offer the ability to specify exactly how the predictor variables interact with each other and the outcome.

Depending on the number of hidden units, the neural network model may include a much larger number of parameters than the logistic model. The total number of parameters in the network can be calculated as $H \cdot (K + 1) + H + 1$, where H denotes the number of hidden units (with 1 hidden layer and 1 output) and K denotes the number of variables in the model. For each hidden unit, a different weight (coefficient) is fitted for each variable and the intercept. For each output unit, a weight is also calculated for each unit in the hidden layer and the intercept in the hidden layer. For instance, a neural net

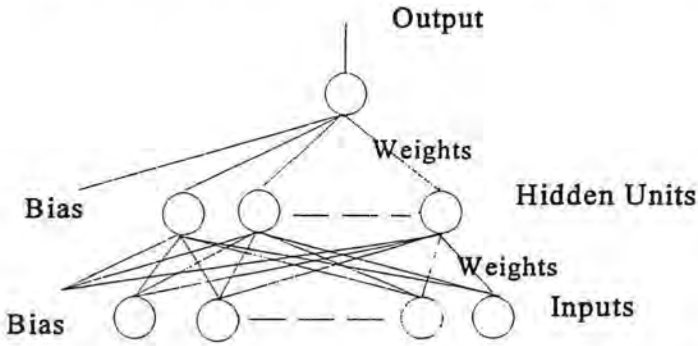

Figure 2. A network for anayzing binary outcomes. (From Landsittel, D.P., Gardner, L.I., and Arena, V.C.)

with 4 inputs and 10 hidden units will have 61 parameters to fit. The fully specified logistic model with 4 variables will have only 15 parameters to fit. These factors may lead to a greater possibility of overfitting random associations with neural networks. Theoretical considerations concerning the balance between maximizing accuracy and minimizing bias are published elsewhere (Geman, Bienstock, and Doursat, 1992).

As with standard regression methods, model complexity becomes especially problematic when the number of covariates is relatively large compared to the number of observations in the data set. Although no specific guidelines exist for calculating the required sample size of the training data set (in relation to model complexity), an adequate sample size for a standard regression method would not necessarily provide sufficient numbers for neural network analysis due to the greater number of parameters in the network model. Research in selecting of an adequate training set is not well developed. Other past publications discuss general considerations such as balancing precision and bias, and satisfying asymptotic properties (Geman *et al.*, 1992; White, 1989).

Optimal network weights can be determined through iterative numerical methods, such as back-propagation (Rumelhart *et al.*, 1995). Using random initial weights, the deviance (or error) of the model is calculated and the weights are updated based on a gradient descent learning rule. The process is continued until the deviance of the model is minimized. This procedure is often referred to as training the network. Since such routines may converge to a local minimum, we implemented two techniques, weight decay and committees of networks, to modify training (Ripley, 1995). Weight decay (Ripley, 1993) adds a penalty term to the deviance to improve convergence. With committees of networks (Rumelhart *et al.*, 1995), the predicted output is determined using five networks with different initial weights. The final output is calculated as the mean output of the five individual networks.

METHODS

For this analysis, we simulated data sets based on known associations between the outcome (back injury present or absent) and the predictor variables. The simulated data was generated to represent injury over a given period of time. Equal follow-up was therefore assumed. Simulated data sets were utilized to control for random associations which might occur in any single data sets. Repeated simulations allow us to better describe the true variability of classification results over many iterations. Simulating data also guarantees that the test data is truly independent of the training data. Any improvement in classification accuracy can then be attributed to specific known associations/data structures specified by the simulation conditions. Since neural nets are not restricted to a linear model in any scale, and implicitly fit interactions through the use of hidden units, overfitting is more likely than with logistic regression. In a simulation study we can assess classification accuracy under different known associations. In this simulation we specified both non-linear and completely random associations.

Based on the literature related to back injury risk factors, four different predictor variables (experience in years, body mass index in kg/m^2, percentage time spent lifting, and percentage of time in non-neutral trunk postures) were selected to be used in these simulations. The number of variables (four) in this study is limited by computational demands. These particular covariates were chosen since their effect on the probability of back injury has been established (see methods) but the exact nature of the (probably non-linear) associations is unclear, thus motivating the implementation of neural networks.

All variables were randomly generated from a multivariate normal distribution. Body mass index was generated independently ($\mu = 27$, $\sigma = 4$) from the other predictors. Experience ($\mu = 3$, $\sigma = 1$) was negatively correlated ($\rho = -0.7$) with both the percentage of time spent lifting and the percentage of time spent bending/twisting, implying that more experienced workers spend less time in material handling tasks. The percentage of time spent lifting ($\mu = 30$, $\sigma = 8$), and the percentage of time spent bending/twisting ($\mu = 30$, $\sigma = 8$) were generated with a positive correlation ($\rho = 0.7$). The distributions and parameters used to simulate these data were specified based on empirical frequency distributions from data sets currently being collected and analyzed. Simulated data was truncated at zero in the very rare instances were negative values were generated.

In the first set of simulations the association between the predictor variables and injury was completely random. Injury was randomly generated as a Bernoulli variable with probability of injury equal to 0.2, regardless of any covariate values. In these simulations we expected the classification accuracy to be no better than chance. Workers with predicted probabilities greater than 0.2 were classified as high risk for injury. One thousand (training) data sets, each with a sample size of 100, were randomly generated and used to fit the logistic and neural network models. The percentage of individuals correctly classified, and the percentage of false positives and false negatives were reported using both methods. Confidence intervals were determined by the 5th and 95th percentiles of the results from the 1000 simulations. To assess generalization of these models, an additional 1000 (test) data sets were generated using the same distributions and association. Classification results for the test data were reported using the models fit with the training data.

In the second set of simulations, a non-linear association was specified between injury and each of the risk factors. The relationships used to generate these associations were motivated by findings in the relevant epidemiologic and ergonomic literature. The underlying probability of injury for each worker was calculated using the following assumptions. Injury status was randomly generated from a Bernoulli distribution with the specified probability of injury.

1. Less experienced workers experience higher back injury rates (Kelsey and Golden, 1988; Kraus *et al.*, 1996).

2. Workers with less than, or greater than optimal body mass index experience higher back injury rates (Kelsey and Golden, 1988).

3. Workers who lift frequently experience higher back injury rates (Burdorf, 1992; Kraus, *et al.*, 1996).

4. Workers who bend or twist frequently experience higher back injury rates (Burdorf, 1992; Kelsey and Golden, 1988; Punnett *et al.*, 1991).

5. Workers who lift and bend or twist frequently experience an interactive effect.

We specified a baseline risk of 0.05 to generate the probability of back injury for each individual worker. To incorporate the previously mentioned assumptions, each worker's risk for back injury was increased by some increment for the level of each risk factor present. For instance, the risk of back injury was additively increased by 0.10 for workers with less than 1 year of previous experience, and by 0.05 for workers with less than 2 years of experience (based on assumption 1 above). Increased risks for different levels of each variable are listed in Table 1. For individuals with a BMI greater than 30, or less than 20, the additional risk of back injury increases linearly with an increase in BMI. Similar associations are specified with percent of time spent lifting and percent of time spent bending or twisting. An interactive effect was simulated for individuals who lift, and bend or twist frequently (greater than 30% of the time). The magnitude of this effect, which is described in Table 2, differs depending on the level of the worker's body mass index and experience. The increased risk is highest for workers with higher than optimal body mass index and less than one year of experience.

Based on each individual's covariates, their probability for back injury was calculated using the associations listed in Table 1 and Table 2. Each worker's injury status was then randomly generated from a Bernoulli distribution with the appropriate probability of injury. Workers with a predicted probability of injury greater than 0.2 were again classified as high risk. One thousand (training) data sets, each with a sample size of 100, were randomly generated and used to fit the logistic and neural network models. Classification tables were calculated with both neural networks and logistic regression for each simulation. To assess generalization of these models, an additional 1000 (test) data sets were generated using the same distributions and association. Classification results for the test data were reported using the models fit with the training data.

Two different logistic regression models were used in each simulation to identify high-risk populations. We specified both the main effects model and the full model with all possible interactions. Since the inclusion/deletion of

Table 1. Simulated increases in the probability of back injury by risk factor.

Variable	Category	Increased risk
Previous experience (in years)	<1	0.10
	≥1, <2	0.05
Body mass index (BMI)	<20	(20-BMI)/100
	≥20, <30	0
	≥30	(BMI-30)/100
% Lifting (%L)	>30	(%L-30)/100
% Bending/twisting (%B)	>30	(%B-30)/100

Table 2. Simulated Interaction between risk factors.

Body mass index (BMI)	Experience (in years)	Increased risk
<20	<1	0.08
	≥1, <2	0.06
	≥2	0.04
≥20, <30	<1	0.06
	≥1, <2	0.04
	≥2	0.02
≥30	<1	0.10
	≥1, <2	0.08
	≥2	0.06

interaction terms cannot be controlled in neural networks, the full logistic model provides the closest possible comparison. The main effects model is also fit for illustrative purposes. Results of other logistic models are not relevant to this comparison. Both the logistic and neural net models were fit using continuous variables.

Since the simulated data structure is completely known, a logistic model could be fit to model the exact associations which are used to generate the data. Such an analysis would undoubtedly produce more accurate results with logistic regression. The specific objective of these simulations, however, was to assess the ability of neural networks to identify high risk populations in the case where the underlying data structure is unknown. Therefore, for the purposes of this study, the covariate values were left as continuous, and more complex parameters were left out of the logistic model.

The data sets generated here can only be considered linear and multiplicative if the cut points for determining probability of injury are known a priori (*i.e.*, if the underlying structure of the data is known). For the purposes of this study, the analysis conducted does not assume any such knowledge and therefore treats the associations as unknown and essentially non-linear. The variables were therefore specified as strictly continuous in each model. Truly non-linear associations were not attempted. The authors limited the simulations to associations which could be easily justified as realistic in this setting.

RESULTS

In the first set of simulations, we analyzed data generated from a completely random association. The percentage correctly classified (%CC), percentage of false positives (%FP), and percentage of false negatives (%FN) were reported (Table 3). Neural networks correctly classified 80% of the injured workers in the training set as high risk. The main effects and fully specified logistic models correctly classified 60 and 70%, respectively, of the observations. Neural networks correctly classified injury status in 55% of the workers in the test data, as compared to 80% of the workers in the training data. The main effects and fully specified logistic models correctly classified 52 and 56%, respectively, of the observations in the test data. Results concerning the test set of random associations indicate that, for 1000 simulations of sample size 100, considerable variability in classification results exists. Given no true association in an independently generated data set, one would expect 50% of the injured to be classified as high risk.

In the next set of simulations, we analyzed data generated from the previously described non-linear associations. The percentage correctly classified (%CC), percentage of false positives (%FP), and percentage of false negatives (%FN) were reported (Table 4). Neural networks correctly classified an average of 85% of the workers in the training data. The main effects and fully specified logistic models correctly classified 74 and 79%, respectively, of the observations. The percentage of workers correctly classified with neural networks was again substantially lower using the test data (67%), as compared to results using the training data (85%). The main effects and fully specified logistic models correctly classified 71 and 69%, respectively, of the observations in the test data.

DISCUSSION

Neural networks have been implemented in past studies to identify high-risk populations in the health care setting (Duh *et al.*, 1998b; Koutsoukos *et al.*, 1994; Tu and Guerriere, 1993). This study represents the first application of neural networks to occupational injury epidemiology. Results from our simulations show that neural networks do not provide any benefit over standard statistical methods in identifying populations at high risk for back injury for these particular simulation conditions, *i.e.*, non-linear associations with a lim-

Table 3. Classification of completely random associations.

Model	Data	%CC		%FP		%FN	
		Mean	95% CI	Mean	95% CI	Mean	95% CI
Main effects-logistic	Training	0.60	0.36,0.80	0.73	0.65,0.82	0.14	0.09,0.21
	Test	0.52	0.28,0.74	0.80	0.68,0.91	0.20	0.10,0.30
Full model-logistic	Training	0.70	0.53,0.83	0.64	0.53,0.73	0.10	0.05,0.15
	Test	0.56	0.40,0.70	0.80	0.69,0.91	0.20	0.12,0.29
Neural network	Training	0.80	0.64,0.93	0.48	0.29,0.61	0.02	0.00,0.07
	Test	0.55	0.38,0.70	0.80	0.69,0.90	0.29	0.12,0.20

Table 4. Classification of non-linear associations.

		%CC		%FP		%FN	
Model	**Data**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**
Main effects-logistic	Training	0.74	0.62,0.86	0.64	0.52,0.75	0.09	0.04,0.13
	Test	0.71	0.57,0.82	0.68	0.52,0.84	0.11	0.04,0.18
Full model-logistic	Training	0.79	0.68,0.90	0.55	0.42,0.67	0.06	0.03,0.10
	Test	0.69	0.57,0.79	0.73	0.58,0.89	0.13	0.06,0.21
Neural network	Training	0.85	0.74,0.95	0.45	0.27,0.58	0.01	0.00,0.04
	Test	0.67	0.54,0.79	0.73	0.58,0.87	0.12	0.04,0.19

ited sample size and a limited number of variables. These findings are consistent with recent epidemiologic studies (Duh *et al.*, 1998b; Ripley, 1994), which indicated that neural networks may provide only equivalent prediction results to logistic models and other regression techniques for common biostatistical settings.

In simulations of a completely random association, neural networks, despite the lack of any true relationship between predictors and injury status, correctly identified injured workers as high-risk 80% of the time. Utilizing even the fully specified logistic model led to results much closer to those expected under a completely random association. For the non-linear association, when using the actual training data to obtain classification results, the percentage correctly classified with neural networks appears slightly higher (although the CIs overlap) than the percentage obtained with logistic regression (Table 4 — 85% vs. 79% and 74%). When using the test data, however, the percentage correctly classified is slightly greater with logistic regression (71 and 69% vs. 67%). The network model likely overfits the true association since neural networks do not allow the user to specify the nature of the association or exclude interaction terms from the model.

Results underscore the importance of using cross-validation methods to modify network training based on test set data and/or obtaining classification results on the independent test set. (Cross-validation methods were not implemented here due to the extremely computational nature of the simulations.) Even though the differences between results using the training set and results using the test set were much greater with neural nets, classification of the training data is still biased with logistic regression. Using the full model, the percent correctly classified was 10 to 15% greater with the training data. Even using the main effects model the percent correctly classified was greater with the training data (although not substantially different). Thus, although such issues are most relevant to neural nets, results serve to motivate the use of an independent test set for prediction with even standard statistical methods. The percentage of false positives and false negatives using the test data was very similar with each of the three models.

Future studies should address the ability of neural networks to identify high-risk populations under different assumptions. In this study, we generated data sets from a particular multivariate normal distribution and a single set of assumptions regarding the association between the predictor variables and injury status. The sample size and number of variables were held constant. Additional simulations should examine variations in these parameters. Very few studies have quantitatively addressed the effect of variations in network parameters or attempted to evaluated the utility of neural nets for different types of data sets (Duh *et al.*, 1998a). Analysis done by Ripley (1995), for instance, indicates little difference between neural nets fit using 3, 5, or 8 hidden units, although weight decay had a significant effect on model fit. Results were only demonstrated for a single data set with 100 observations. Although other studies have done some analysis to determine the relative importance of such factors (Duh *et al.*, 1998a; Duh *et al.*, 1998b; Lippmann and

Shahian, 1997; Ripley, 1994; Geman *et al.*, 1992), these studies do not provide clear guidelines regarding the inter-relationship between model structure, sample size, and other factors in risk assessment. Using the results of this study, researchers should run further analyses/simulations to investigate such issues.

Some generalizations can be made about possible/probable ramifications. A greater number of hidden units increases the network's ability to transform the data and achieve linear separability (Hertz *et al.*, 1991; Levine, 1991). Specifying networks with more hidden units or hidden layers (*i.e.*, more parameters to fit) would therefore likely lead to more accurate results in terms of identifying injured workers as high risk, although overfitting will likely worsen (Landsittel, 1997).

For the purposes of this analysis we generated injury status assuming equal follow-up. In most cases, where differential follow-up exists, the injury rates (rather than injury status) are analyzed. Currently, methods to accomplish this with neural networks are not available, although several publications have recently addressed implementing neural nets for survival analysis (Faraggi and Simon, 1995; Liestol, Anderson, and Anderson, 1994). Estimating levels of risk associated with particular categories of a given variable is also very difficult with neural networks. Because the weights associated with hidden units are not directly interpretable as coefficients for a particular variable, assessing the magnitude and direction of a particular variable's effect on the outcome is problematic.

Results of this study do not completely answer the research question of when to use neural networks for occupational injury risk assessment. The results do, however, indicate that departures from linearity in a logit scale do not provide sufficient motivation for implementing neural network analysis. Researchers should first decide whether the underlying structure of the data can be reasonably described through conventional methods. If so, standard regression methods will likely provide adequate results. In situations where this cannot be accomplished, neural networks may still prove useful since the user only specifies which variables are included in the model. Further investigations of specific conditions where neural nets are most useful are needed.

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Relative Risk of Involuntary Injuries Among Currently Employed Adults in the U.S.

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ABSTRACT

It can be very informative to compare the risk of injury for different occupations, places where accidents happen, demographic variables, and other characteristics. However, most epidemiologic literature shows that multiple logistic regression or odds ratio were commonly used to compare the relationship between the variables on two or more levels. A multiple logistic regression could be used for multiple comparisons assuming that the model correctly reflects the situation at hand. But it might not be a true assumption. Assuming no model, we defined the relative risk to compare risks of injury for different occupations, and applied this method to the data collected by the National Center for Health Statistics (NCHS) National Health Interview Survey (NHIS). This application showed that the relative risk of injury varied by occupation and by place of accident, sex, race, and age.

Key Words: occupational injuries, model independent analysis, sample estimation, test of hypothesis

INTRODUCTION

Unintentional injury occurs in a wide variety of places and occupations. Injury is a serious health and economic problem in industry. Injury accounted for 19% of all Worker's Compensation claims in the United States in 1979 (Klein, Jensen, and Senderson, 1984; Rowe, 1983), and Worker's Compensation claims have been increasing continually in recent years (Frank, Pulcins, Kerr, Shannon, and Stansfeld, 1995).

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A total of 6.6 million injuries and illnesses were reported in workplaces in private industry during 1995 (U.S. BLS, 1997). The estimated cost resulting from injury was approximately $145 billion in the United States (Leigh and Landrigan, 1997).

The National Council on Compensation Insurance estimated that expenditures for Worker's Compensation were increasing every year (Rowe, 1983; Leigh and Landrigan, 1997). Injuries are one of the leading causes of lost work days in the United States (Loser and Volinn, 1991; NCHS, 1995). Leavitt (1992) found that heavy physical work was the most frequent cause of injuries among currently employed.

The plans for the prevention of occupational injuries have to be based on data that illuminate the nature and magnitude of these injuries. Injury epidemiology is an important part of public health concerns and became one of the focus areas in the healthy people 2000 objectives (USDHHS, 1996). In order to prevent these costly injuries, one step is to obtain as much information on occupational injuries as possible. The more we know about them, the better we can prevent them. To this end, we developed a simple method for comparing the relative risk of injury for different occupations, places of work, and other characteristics.

To present the concept and applications of relative risk, we introduced a sampling and classification of occupations in the 2nd section. In the 3rd section, we define the relative risk of involuntary injury, and present an estimator. Its variance and testing of significance are presented in the Appendix. In the 4th section, this method was applied to the NCHS data, and the risks of injury are shown in the ensuing tables. Finally, we have some comments in Section 5.

SAMPLE

The National Health Interview Survey (NHIS) is a continuous, cross-sectional survey of the U.S. civilian non-institutionalized population (NCHS, 1995). It is conducted annually by the National Center for Health Statistics (NCHS), part of the Centers for Disease Control and Prevention. In 1994, the basic health and demographic questionnaire included questions about the unintentional injuries and other medical conditions of the persons living in the sample households. This survey provided the data for this study. Basically the segments were selected through probability proportional to the population size, and persons in each segment were selected with equal probability. The details of sampling procedures, including the design and the questionnaire, are described in detail elsewhere (NCHS, 1995; U.S. Bureau of the Census, 1978).

The 1994 National Health Interview Survey sample included about 116,000 persons, of which about 53,300 persons were 18 years of age or older and currently employed. Only 3,200 of these 53,000 persons reported an unintentional injury. Each person was counted only once if the person had more than one injury in the same accident. Each sample person was weighted to represent the population from which this person was selected. An estimated 7.41 million workers among 122.9 million currently employed (6.03%) were injured in 1994.

All the variables in the study are based on the family information obtained from one adult sampled from each household. Occupation was coded according to the 1980 Classified Industries and Occupations of the U.S. Bureau of the Census (U.S. Bureau of the Census, 1980). For this study, seven occupation groups were used:

1. ***Managerial*** and professional specialty occupations combining, "Executive, administrative and managerial occupations" and "Professional specialty occupations"

2. ***Technical***, sales, and administrative support occupations combining "Technicians and related support occupations," "Sales occupations," "Administrative support occupations, including clerical."

3. ***Service*** occupations combining "Private household occupations," "Protective service occupations," and " Service occupations, except protective and household."

4. ***Farming***, forestry, and fishing occupations

5. ***Precision*** production, craft and repair occupations

6. ***Operators***, fabricators and laborers combining, "Machine operators, assemblers and inspectors," "Transportation and material moving occupations," and "Handlers, equipment cleaners, helpers and laborers."

7. ***Unknown*** (includes never worked, refused, classified, etc.)

The persons injured were first divided into two groups, those injured while working and those injured while not working. Nine places of injury are included in the NHIS, regardless working or not working:

1. at ***home inside*** a house,

2. at ***home adjacent*** premises,

3. ***street and highway*** including roadway and public sidewalks,

4. ***farm***,

5. ***industrial*** place including premises,

6. ***school*** including premises,

7. *place of recreation* and sports, except school,

8. *other,*

9. *unknown.*

For completeness, a tenth "place," *not injured,* was included.

METHOD

For this study, the relative risk is defined as the ratio of the percent of persons injured in one occupation group to that of other occupation groups. We use the parameter $R_{o/r}$ for the relative risk in the population, and $R_{o/r}$ compares the percent of the population in occupation "o"who are injured to that of the reference occupation "r" when $0 = 1, \ldots, 0$:

$$R_{o/r} = \frac{\text{percent of persons in the population injured in occupation o}}{\text{percent of persons in the population injured in reference occupation r}}$$

The parameter $R_{o/r}$ is estimated by a sample estimator $r_{o/r}$:

$$r_{o/r} = \frac{\text{percent of persons in the sample injured in occupation o}}{\text{percent of persons in the sample injured in reference occupation r}}$$

We chose one of the occupations as the reference group "r", depending on the needs of the analysis. The percent of persons injured in the reference occupation group were compared to the percent of persons injured in another occupation group "o". There are the same number of relative risks as the number of occupations to be compared. The relative risk of reference occupation is 1, when the percent of reference occupation was divided by itself. The relative risks of the other occupations would fluctuate around 1. If the $r_{o/r}$ of one specific occupation is larger than 1, the persons in that occupation would be more likely to be injured than those in the reference occupation. On the other hand, if the $r_{o/r}$ is smaller than 1, they would be less likely to be injured.

For example, assume 40% of persons from the *manufacturing* occupation group were reported injured, while 10% of persons from the *sales* occupation group were reported injured. If both occurred at an *industrial* place, and the *sales* occupation group was selected as the reference occupation, the relative risk for the two occupation groups was 4 at an *industrial* place. There were 4 injuries per 100 persons in the *manufacturing* occupation group for every 1 injury per 100 persons in the *sales* occupation group, at an *industrial* place. The relative injury risk of injury for *manufacturing* workers was four times that of *sales* workers.

VARIANCE

The NHIS sample design is complex, the data are collected in houshold interviews, and the estimates are subject to a variety of sampling and non-sampling errors. The actual sampling design and estimation processes must be considered to obtain the variance of the relative risk based on such data. The Appendix shows the calculation of the variance of the estimator $r_{o/r}$ derived under certain assumptions.

There are different approaches which can be used to derive the variance, including resampling methods and model-based methods. The variance derived in the Appendix is based on a design method along with correlation models and the Taylor expansion.

TESTS OF HYPOTHESIS

We can standardize the relative risk under a null hypothesis with the variance obtained by SUDAAN (Shah, Barnwell, Bieler, 1996) or by the method suggested in the Appendix.

The standardization allows us to assume a normal distribution of the test statistic to test the null hypothesis. Alternatively, an interval estimation could be used to see if the value in the null hypothesis belongs to such an interval. Interval estimation is especially useful when the sample size is too big or too small.

When the relative risks were widely scattered or skewed to one side, or when variables are too large or too small, we can stabilize them by taking the log. The log numbers are often easier to handle than the original numbers, as discussed in Appendix.

We set up a null hypothesis that the log of the relative risk equals the log of the relative risk under the null hypothesis. The variance of the log relative risk is the same as that of original relative risk except R is replaced by log R. The result of both approaches, original relative risk and log of relative risk, is the same. If one test suggests accepting or rejecting the null hypothesis, the other test would suggest the same.

RELATIVE RISK (RR) VS. ODDS RATIO (OR)

An OR differs from a RR, but they often are very close. The OR compares the odds of two events in a 2×2 table. Suppose that A is the attribute for two rows, A and not A and B is the attribute for two columns, B and not B. The not A and not B are the complements of A and B, respectively. OR is the ratio of two odds, $p(B|A)/p(\text{not } B|A)$ over $p(B|\text{not } A)/p(\text{not } B|\text{not } A)$.

The RR compares any two probabilities or percents in a K by L matrix $(K, L \geq 2)$. It is not restricted to a 2×2 table. First we calculate the percent in each column, and then compare two percents from different rows as seen in Tables 1 and 1a. The $RR = p(B|A)/p(B|\text{not } A)$ for the 2×2 table. We use the 2×2 table to find similarities and differences between OR and RR.

Table 1. Number of currently employed persons in thousand row-wise, percent injured by occupational groups working or not (standard errors), United States, 1994.

Occupation group	No. of employed and injured persons (in thousands)	Percent injured while working	Percent injured while not working
Managerial	34,940 (446)	1.735 (0.11)	3.96 (0.17)
Technical	36,312 (416)	1.743 (0.11)	3.64 (0.15)
Service	15,992 (272)	2.80 (0.22)	3.69 (0.25)
Farming	3,052 (117)	2.46 (0.39)	2.60 (0.43)
Precision	12,549 (223)	4.09 (0.28)	3.45 (0.28)
Operators	16,794 (296)	4.29 (0.25)	3.06 (0.20)
Unknown	3,274 (157)	1.03 (0.26)	2.15 (0.38)
Total	122,912 (989)	2.46 (0.07)	3.57 (0.09)

Table 1a. Column-wise relative risk among workers by occupational group groups working or not, and (standard errors), United States, 1994.

Occupation group	Relative risk while working	Relative risk while not working
Managerial[a]	1.00 (0.11)	1.00 (0.17)
Technical	1.01 (0.16)	0.92 (0.23)
Service	1.61 (0.25)	0.93 (0.30)
Farming	1.42 (0.41)	0.66 (0.46)
Precision	2.36 (0.30)	0.87 (0.33)
Operators	2.47 (0.27)	0.77 (0.26)
Unknown	0.59 (0.28)	0.54 (0.42)

[a] Reference.

Let the 2×2 table include four cells, n_{11} and n_{12} for A in the first row, and n_{21} and n_{22} for not A in the second row. Then:

$$OR = (n_{11}n_{22})/(n_{12}n_{21}) \quad \text{and} \quad RR = (n_{11}n_{21} + n_{11}n_{22})/(n_{11}n_{21} + n_{12}n_{21})$$

The OR becomes the RR when we add the same number n_{11} n_{21} to the numerator and denominator of the OR. If the occurrence of B is unlikely, both the OR and the RR would not differ much, as seen in the Tables 3b, 4b, and 5b.

Table 2. Percent distribution of persons injured over places of injury for each occupation, and (standard error), United States, 1994.

Place of injury	Managerial	Technical	Service	Farming	Precision	Operators
Home inside	0.56 (0.06)	0.55 (0.06)	0.56 (0.09)	0.30 (0.15)	0.19 (0.06)	0.30 (0.07)
Home around	0.57 (0.06)	0.45 (0.05)	0.43 (0.07)	0.13 (0.09)	0.62 (0.11)	0.59 (0.08)
Street and highway	1.76 (0.11)	1.83 (0.11)	1.92 (0.19)	1.52 (0.35)	1.80 (0.21)	1.67 (0.16)
Farm	0.04 (0.01)	0.03 (0.01)	0.07 (0.04)	1.42 (0.30)	0.13 (0.05)	0.08 (0.03)
Industrial	0.89 (0.08)	1.10 (0.09)	1.70 (0.16)	0.75 (0.22)	3.25 (0.25)	3.39 (0.22)
School	0.35 (0.05)	0.14 (0.03)	0.31 (0.09)	0.06 (0.07)	0.06 (0.04)	0.04 (0.03)
Place of recreation	0.68 (0.07)	0.62 (0.07)	0.47 (0.10)	0.30 (0.15)	0.51 (0.09)	0.51 (0.09)
Other	0.81 (0.08)	0.65 (0.08)	0.99 (1.13)	0.45 (0.18)	0.81 (0.12)	0.77 (0.12)
Unknown	0.04 (0.02)	0.01 (0.01)	0.05 (0.03)	0.13 (0.09)	0.06 (0.03)	0.01 (0.01)
No injury	94.30 (0.20)	94.61 (0.19)	93.51 (0.32)	94.95 (0.60)	92.57 (0.37)	92.65 (0.34)
	100%	100%	100%	100%	100%	100%

Table 2a. Relative risks of injury for occupations at each place of injury, United States, 1994. managerial occupation used as reference.

Place of injury	Managerial[a]	Technical	Service	Farm	Precision	Operators
Home inside	1.00	0.98	1.00	0.54	0.34	0.53
Home around	1.00	0.79	0.75	0.23	1.09	1.04
Street and highway	1.00	1.04	1.09	0.87	1.02	0.94
Farm	1.00	0.75	1.75	35.50	3.25	2.00
Industrial	1.00	1.24	1.91	0.84	3.65	3.81
School	1.00	0.40	0.89	0.17	0.17	0.11
Recreation place	1.00	0.91	0.69	0.44	0.75	0.75
Other	1.00	0.80	1.22	0.56	1.00	0.95
Unknown	1.00	0.50	1.25	3.25	1.50	0.25
Not injured	1.00	1.00	0.99	1.01	0.98	0.98

[a] Reference.

Table 3. Number of currently employed persons in thousands, percent injured groups working or not, by race, and (standard errors), United States, 1994.

Race	No. of currently employed persons	Percent injured while working	Percent injured while not working
Black	13,249 (425)	1.18 (0.21)	3.34 (0.26)
Non-black	109,662 (1,004)	2.54 (0.08)	3.59 (0.09)
All	122,912 (989)	2.46 (0.07)	3.57 (0.09)

Table 3a. Relative risk of currently employed persons working and by race.

Race	Injury while working	Injury while not working
Black[a]	1.00	1.00
Non-black	2.15	1.08

[a] Reference.

Table 3b. Relative risk (RR) vs. odds ratio.

	All injured		Not injured	
Race	Percent	RR	percent	
Black[a]	4.52	1.00	95.48	Odds ratio of injury of non-black = (6.13 × 95.48)/(4.52 × 93.87) = 1.38
Non-black	6.13	**1.36**	93.87	Relat. risk of non-black injury = 1.36

[a] Reference.

The OR = 1 implies that the odds of the occurrence of B is about the same regardless of the presence of A. The RR = 1 implies that the risk of the occurrence of B is about the same regardless of the pressure of A. The RR can be used to compare any two cells provided both percents are based on the respective total.

Table 4. Number of currently employed persons in thousands, percent injured groups working or not, by age, and (standard errors), United States, 1994.

Age	No. of currently employed persons	Percent injured while working	Percent injured while not working
18–44	83,925 (833)	2.33 (0.09)	3.46 (0.10)
45+	38,987 (413)	2.75 (0.12)	3.79 (0.16)
All	122,912 (989)	2.46 (0.07)	3.57 (0.09)

Table 4a. Relative risk of injured groups working or not and by age.

Age	Injured while working	Injured while not working
18–44[a]	1.00	1.00
45+	1.18	1.10

[a] Reference.

Table 4b. Relative risk vs. odds ratio of injury.

	All injuries		Not injured	
Age	%	RR	%	
18-44	5.79	1.00	94.21	Odds ratio of injury of old = $(6.54 \times 94.21)/(5.79 \times 93.46) = 1.14$
45+	6.54	1.13	93.46	Rel. risk of old injury = 1.13

EXAMPLES

We applied the relative risk (RR) of injury to the NHIS data. Table 1 shows the row-wise percent of currently employed persons injured while working or not working by occupation group. Using Table 1, the column wise relative risks in Table 1a were computed. The *managerial* group was the reference group "r" to which the other occupations were compared.

While working, among the six occupation groups, the highest RR was reported by *operators*, and the lowest RR reported by the *managerial* group. For RR = 1 among *managerial* workers, there would be 1.01 risk of injury for *technical* workers, 1.6 risk for *service* workers, 1.4 risk for *farm* workers, 2.36 risk for *precision* workers, and 2.47 risk for *operators*.

Table 5. Number of currently employed persons in thousand, percent injured groups working or not, by sex and (standard errors), United States, 1994.

Sex	No. of currently employed persons	Percent injured while working	Percent injured while not working
Male	66,941 (566)	3.14 (0.10)	3.37 (0.11)
Female	55,971 (516)	1.66 (0.08)	3.80 (0.13)
All	122,912 (989)	2.46 (0.07)	3.57 (0.09)

Table 5a. Relative risk of injury by whether while working or not and by sex.

Sex	Injured while working	Injured while not working
Male[a]	1.00	1.00
Female	0.53	1.13

[a] Reference.

Table 5b. Relative risk vs. odds ratio of injury.

	All injured		Percent	
Sex	Percent	RR	not injured	
Male[a]	6.51	1.00	93.49	Odds ratio of injury of female = (5.46 × 93.49)/(6.51 × 94.54) = 0.83
Female	5.46	**0.84**	94.54	Rel. risk of female injury = 0.84

[a] Reference.

While not working, compared to the RR of 1 for the reference occupation, the RR of the other occupations fell below 1. The highest RR was reported by managerial workers.

Table 2 includes the column-wise percent of persons injured at different places according to whether working or not working. Each column shows the percent for an occupation group, and the column sum is 100%. For example, the *Operators* are divided among the six places of injury, unknown, and not injured. The percent distribution of injuries among operators is 3.39% in industrial places, 1.67% in streets and highways, 0.89% at home (inside and around the household), 0.77% in other places, 0.51% in recreational places, 0.08% at farming, 0.04% at school, 0.01% for unknown, and 92.65% of them were not injured, and similarly for the other occupation groups.

From Table 2, using the *managerial* occupation group as the reference, we calculate the RRs for each row, dividing the percent injured in a row by the percent injured in the reference occupation. The RR of the reference occupation is 1, and others fluctuate about 1. Each row in Table 2a shows the RR of injury for 6 occupations at a particular place of injury.

For injuries on the *street and highway* in Table 2a, when compared to RR = 1 for the *managerial* occupation group, for the *technical* occupation it was 1.04, for the *service* occupation group it was 1.09, for the *farm* occupation group it was 0.87, for the *precision* occupation group it was 1.02, and for the *operator* occupation group it was 0.95. The RRs in *street and highway* was about the same except the *farm workers* with the lower RR score of 0.87. It appears that most of us were exposed to injuries in the *street and highway* with about the same RR except *farm workers.*

The first row included the RRs *inside home* among six occupations. Compared to the *managerial* occupation, the RRs of injury *inside home* were 0.98 for *technical* occupation, 1.00 for *service* workers, 0.54 for *farm workers,* 0.34 for *precision* workers, and 0.53 for *operators.* Those of *precision* occupation group reported the lowest RR at *home.*

The fifth row showed the RRs at *industrial place.* All the RRs except *farm workers* were higher than one: 1.24 for *technical,* 1.91 for *service,* 0.84 for *farm workers,* 3.65 for *precision,* and 3.81 for *operators.* The persons in the of *precision* and *operator* occupation groups reported a higher RR of injury at *industrial places* with 3.65 and 3.81, respectively, almost four times of the *managerial* workers.

In general, at *industrial places,* the blue color workers - *service, precision, and operator* - had a higher RR of injury and the white color workers of *managerial* occupation and *farm workers* had lower RR . This trend was reversed for the RR *at home.*

Farm workers' RR *at a farm* recorded as 35.5 times that of the *managerial* occupation, the highest RR among those of other occupations. It implied that *farm workers* were injured most *at a farm.*

The RR of injury *at school* was very low for most occupations, 0.17 for *farm workers,* 0.17 for *precision* workers, 0.11 for *operators.* Only *service* workers reported 0.89, closer to the RR of the *managerial* occupation.

The RR in the *recreational area* is 0.91 for *technical* workers, 0.69 for *service* workers, 0.44 for *farm workers,* 0.75 for both *precision* workers and *operators. Managerial* workers reported the highest rate of injury at *recreational places* among these six occupations.

Table 3 shows the number of employed persons and percent of injuries by race and by working and not-working. Table 3a included the RR obtained from Table 3. Black was the reference point with RR = 1 to which non-black RR was compared. While working, non-black workers reported an RR of injury 2.15

times higher than black workers. But, while not working, the RR of non-black was 9.93 slightly lower than blacks.

Table 4 shows the numbers and percent of persons injured by age, 18-44 years and 45+.

Table 4a was constructed from the percents in Table 4. The younger group was used as reference to which the older group compared. The RR of injury for the older group was 1.18 while working and 1.10 while not working; both RRs higher than those of the younger group.

Table 5 included the numbers and percents of persons injured by sex, men and women. The corresponding RRs were shown in Table 5a. Compared to men, women reported a lower RR of 0.53 while working, but women reported a slightly higher RR while not working with the score of 1.13. This may imply that men are more likely injured while working, and women are more likely injured while not working.

The Table 3b, Table 4b, and Table 5b are the 2 × 2 tables by injured or not injured and by race, age, or sex, respectively. We calculated OR and RR for each table for comparison. The respective scores of RR and OR were 1.36 and 1.37 in Table 3b for the race, 1.13 and 1.14 in Table 4b for the age, and 0.84 and 0.83 in Table 5b for the sex. These scores are fluctuating little around one. They remained very close to one for both OR and RR because the percent of injury is very low, compared to that of not injured.

One RR score or the difference between two RRs may be tested by interval or a null hypothesis. Log of RR might stabilize the RR scores when they are skewed to one side or scattered around widely as suggested in the Appendix.

DISCUSSION

We may choose the overall percent of persons injured as the reference point instead of the percent of persons injured in one specific occupation group. In this case, we are comparing the percent of persons injured of one occupation group to the percent, of persons injured of all other occupation groups. For example, in Table 1a we choose the managerial occupation as the reference point, but we could have chosen the total of all occupation groups as the reference point. This reference would be the percent of injuries among all currently employed persons. We may also consider a weighted average of the percent of all occupation groups who were injured as a reference point.

The SUDAAN is used to calculate the variances, assuming that the correlation in the sampling cluster is negligible. This may not be true for certain variables. For instance, there would be a strong correlation among members of the family or cluster when we consider the family income or race. In this case, we have to use the variance formula shown in the Appendix.

The relative risk can be applied to other areas in business, mortality, or diseases. For instance, before picking a stock to buy, one may compare the percent of relative profit of this stock to those of other candidates, and then purchase the stock with better relative profit. Another example is the relative risk of getting lung cancer among miners. Considering the percent of miners getting lung cancer as the reference, we may compare it to the percent of miners getting other diseases.

As the NHIS collects yearly data on injury, one might evaluate the relative risk of injury of the working population over time, and develop information systems for surveillance. This would exert pressure for new preventive efforts to target high-risk work sites, and develop specific strategies for injury prevention. This method may help to provide helpful information to develop injury reduction strategies at a workplace.

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APPENDIX

A sample S is taken from the population U. Clusters were selected by pps design and the persons in the cluster were selected by equal probability. The population U included the units $\{U_{oij}\}$ for $i = (1,A)$, $j = (1,B_i)$, and $o = (1,O)$.

Defined the relative risk as $R_{o/r}$ for relative risk of injury at work comparing occupation "o" to reference occupation "r".

The sample $S = \{(i,j): i \in S^*; j \in S_i\}$ where S^* is a set of segments and S_i is the number of persons in segment i. The sample segments are indexed by $i = (1, a)$ and the persons by $j = (1, b_i)$. The subscripts i and j for the population are not the same as the i and j for the sample.

The sample S included a set of sample persons $\{u_{oij}\}$.$\{u_{oij}\}$ are measured by $\{x_{oij}\}$.

$$x_o = \Sigma_{ij} w_{oij} x_{oij}$$

where w_{oij} is the weight of the (oij)-th person, and $x_{oij} = 1$ if the person (oij) is injured and $x_{oij} = 0$ otherwise,

$$w_{oij} = (1/\Pi_{oij})(C_{aij}/S_{aij})$$

where Π_{oij} is the probability of person (oij) included in the sample, and C_{aij} is the known population count in cell a where the ij-th person belongs and S_{aij} is the corresponding sample estimate of C_{aij}.

$$n_o = \Sigma_{ij} w_{oij}, \;\; x_o = \Sigma_{ij} \delta_{oij}$$

where $\delta_{oij} = 1$ if the oij = the person injured, and $\delta_{oij} = 0$, otherwise.

x_o and n_o are the estimated numbers of the injured persons and all persons for the occupation "o". Similarly, x_r and n_r are the numbers of injured persons and all persons, respectively, for the reference occupation "r". Denote the estimator of a sample relative risk by $r_{o/r}$, $0 = 1, \ldots, 0$.

$$r_{o/r} = \frac{\frac{x_o}{n_o}}{\frac{x_r}{n_r}}$$

Let the expected values of x_o, n_o, x_r, n_r be μ_o, μ_{no}, μ_r, μ_{nr}, respectively, and the variances be σ_o^2, σ_{no}^2, σ_r^2, σ_{nr}^2, respectively. Also denote the ratio of percent by $R_{o/r} = R_o/R_r$ in the population, where $R_o = \mu_o/\mu_{no}$ and $R_r = \mu_r/\mu_{nr}$. Taylor expansion of $r_{o/r}$ is

$$r_{o/r} = R_{o/r}\left(1 + \frac{x_o}{\mu_o} - \frac{n_o}{\mu_{no}} - \frac{x_r}{\mu_r} + \frac{n_r}{\mu_{nr}}\right) + O\left(n^{-1}\right)$$

When the occupations are independent, it can be shown that the variance of $r_{o/r}$ is given by

$$\mathrm{Var}\left(r_{o/r}\right) = R^2\left[\frac{\sigma_o^2}{\mu_o^2} + \frac{\sigma_{no}^2}{\mu_{no}^2} - 2\frac{\mathrm{cov}\left(x_o, n_o\right)}{\mu_o \mu_{no}} + \frac{\sigma_r^2}{\mu_r^2} + \frac{\sigma_{nr}^2}{\mu_{nr}^2} - 2\frac{\mathrm{cov}\left(x_r, n_r\right)}{\mu_r \mu_{nr}}\right]$$

where $\mathrm{var}(x_o) = \sigma_o^2$.

Since x_o, n_o, x_r, n_r are the weighted and correlated counts as shown before, and $\Pi_{ij} = \Pi$ for a pps sample S, the variances, σ_o^2, σ_{no}^2 σ_r^2, and σ_{nr}^2 and covariances, $\mathrm{cov}(x_o, n_o)$ and $\mathrm{cov}(x_r, n_r)$, are obtained by Taylor expansion and correlation models. Under correlation assumptions, it can be shown

$$\mathrm{var}\left(x_o\right) = s_{do}^2 n\left[1 + (b-1)\theta\right]/\Pi^2$$

$$s_{do}^2 = \frac{1}{\left(N_o - 1\right)} \Sigma_{i=1,A;\, j=1,Bi}\left(d_{oij} - \overline{D}_o\right)^2$$

where s_{do}^2 is the variance of $d_{oij} = (x_{oij} - R_o s_{oij})$, s_{oij} is the estimated number of persons falling in the age-sex-race cell where the (ij)-th person belongs. θ is the common intracluster correlation between d_{oij} and $d_{oij'}$ for $j \neq j'$ in cluster i. $\overline{D}_o$ is the average of all d_{oij}, and Π the common selection probability of (ij) element for pps sample, N_o is the number of persons with occupation "o" in the population, n is the number of sample units n = ab, and b is the number of units in the cluster when $b_i = b$.

The ratio $R_o = E(x_{oij})/E(s_{oij})$ and $E(d_{oij}) = 0$.

$var(x_o)$ reflects two facts: Taylor expansion of ratio and the intracluster correlation.

Denote the number of persons in the age-sex-race cell where (ij) person belongs by U_{oij} and its sample estimate by S_{oij}. Write the difference by $d^*_{oij} = (U_{oij} - S_{oij})$ and $\overline{D}^*_o$ for the average of all d^*_{oij}. $E(d^*_{oij}) = 0$. θ^* is intracluster correlation between d^*_{oij} and $d^*_{oij'}$ for $j \neq j'$ in cluster i. It can be shown

$$var(n_o) = S^2_{d*o} n\left[1 + (b-1)\theta^*\right]$$

$$S^2_{do} = \frac{1}{(N_o - 1)} \Sigma_{i=1,A;\, j=1,Bi}\left(d_{oij} - \overline{D}_o\right)^2$$

Similarly, the covariance between x_o and n_o can be written as, if injured and not injured are independent,

$$Cov(x_o, n_o) = ns = var(x_o)$$

$n_o = x_o + x_{o1}$. (Injured plus not injured.)

Similarly derive the variances $var(x_r)$ and $var(n_r)$, and covariance $cov(x_r, n_r)$ of the reference occupation "r". Replacing these variances and covariances and correlations with respective sample estimates, we can obtain a sample estimate of $var(r_{o/r})$. Methods of correlation are suggested in a reference (Choi and Landis, 1997).

If the correlations θ and θ^* are all negligible, then the variances and covariances retain only the first term, and we can use SUDAAN to obtain approximations.

The hypothesis $H_o : R_{o/r} = R$ (*e.g.*, R = 1) may be tested with a test statistic

$$Z = \left(r_{o/r} - R\right) \Big/ \left[var\left(r_{o/r}\right)\right]^{1/2}$$

$$\text{or interval} \quad \left(r_{o/r} - 2s\right) \leq R \leq \left(r_{o/r} + 2s\right)$$

If the r's are unstable, scattered around or skewed, taking log may stabilize r's.

Then H_o: log $R_{o/r}$ = log R (*e.g.*, log 1 = 0). Test statistics are

$$Z' = \left(\log r_{o/r} - \log R\right) \Big/ \left[\mathrm{var}\left(\log r_{o/r}\right)\right]^{1/2}$$

and $$\left(\log r_{o/r} - 2s^*\right) \le \log R \le \left(\log r_{o/r} + 2s^*\right)$$

where var(log $r_{o/r}$) is the same as the var($r_{o/r}$) except R is replaced by log R in the formula.

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Work-Related Fatal-Injury Risk of Construction Workers by Occupation and Cause of Death

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ABSTRACT

To assess cause- and occupation-specific risks of work-related fatal injuries among U.S. construction workers, the National Traumatic Occupational Fatalities (NTOF) surveillance system and Current Population Survey were used to obtain injury and employment data for the years 1990 through 1994. Risks were assessed by both rate and working lifetime risk. The occupation found to have the highest fatal-injury rate in construction was electrical-power installers and repairers (96.6 deaths/100,000 workers), followed by structural-metal workers (86.4) and operating engineers (41.0). The occupation found to have the largest numbers of fatalities was construction laborers (1133 deaths), followed by carpenters (408), and construction supervisors (392). The leading causes of death varied by occupation. Construction in general has experienced a decline in fatal-injury rates over the years; however, this decline did not occur equally across occupations and causes of death. The presentation of working lifetime injury risks provides a measure of risk for occupational injuries that can be compared with occupational illness risk assessments. This study is the first to provide a comprehensive national profile of work-related fatal-injury risks among United States construction workers by occupation and cause of death. The results will be useful in focusing research and prevention efforts on specific hazards in high-risk construction occupations.

Key Words: occupational, NTOF, lifetime risk

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INTRODUCTION

Construction remains one of the largest and most dangerous industries in the United States; approximately 930 construction workers were killed by work-related injury annually from 1990 to 1994. However, little information exists on fatality rates risk by occupation within the industry, probably due to the difficulties in assembling data on both fatalities and populations at risk in an industry characterized by a high proportion of small companies and by large turnover in the work force (Dong *et al.*, 1995). The purpose of this paper is to present findings on fatality risk by occupation and cause of death within the construction industry. These findings support the general research requirement, as identified in the traumatic injuries chapter of the National Occupational Research agenda (NORA) document (NIOSH, 1996), for increased work-sector-specific information to drive intervention and prevention strategies. Findings on occupation and cause of death in construction can clearly be used to drive targeted prevention programs within this industry, one of four industries identified in the NORA document as having fatality rates "notably and consistently higher" than all other industries.

There have been three studies which provided limited information on occupational-fatality risks for selected occupations or occupation groups in the United States' construction industry. In a study that used death certificates from 19 states (Robinson *et al.*, 1995), proportionate mortality ratios (PMRs) were calculated for falls, homicide, unintentional poisonings, and fatalities—usually work-related—for selected occupations. A California occupational mortality study (CDHS, 1987) calculated standard mortality ratios (SMRs) by cause of death for selected occupations or occupation groups in California during 1979 to 1981. A study of Census of Fatal Occupational Injury (CFOI) data from 1992 to 1993 reported work-related fatality rates for selected occupations or occupational groups within the construction industry (Pollack *et al.*, 1996). These three studies used only three or four broad categories to describe various injuries, and, consequently, information on more specific causes of death was not provided. Since mortality was only reported for a limited number of occupations and occupational groups, it is possible that some occupations with high risk of fatal injury were missed. It is also possible that high-risk occupations were grouped with low-risk occupations.

The National Traumatic Occupational Fatalities (NTOF) surveillance system, implemented by the National Institute for Occupational Safety and Health (NIOSH), is a census of death certificates for occupational traumatic fatalities in the United States (Jenkins *et al.*, 1993). Prior to 1990, a 1987 computer algorithm had been used on NTOF data to code information on decedents' usual occupation and industry. The 1987 algorithm produced codes that were accurate at the division, or aggregate level (Castillo and Jenkins, 1994). Beginning in 1990, NTOF data were manually coded for detailed industry and occupation using the Bureau of the Census (BOC) classification system (BOC, 1982; BOC, 1992; Fosbroke, Kisner, and Myers, 1997). This improvement in coding detail makes it possible to assess injury risks by detailed occupation within the construction industry. The current study was conducted using 1990–1994 NTOF data and the Bureau of Labor Statistics' (BLS) Current Population Survey (CPS) data to assess the work-related fatality risk of specific construction occupations and to identify cause- and occupation-specific fatality patterns and the trends of such fatalities over the study period.

MATERIALS AND METHODS

The data source used to define occupational fatalities was NTOF data for the calendar years from 1990 to 1994. The NTOF data were collected from all 52 Vital Statistics reporting agencies in the United States. Methods, strengths, and limitations of the NTOF have been well documented elsewhere (Stout, 1988; Jenkins *et al.*, 1993). The inclusion criteria for NTOF are: (1) death resulting from an external cause of injury (E-codes, 800–999) according to the International Classification of Disease, Ninth Revision (ICD-9) (WHO, 1977); (2) victim's age at least 16 years; and (3) a positive response to the death certificate's "Injury at Work?" item.

Employment data were obtained from the Current Population Survey (CPS), a household survey conducted by the Bureau of the Census (BOC) for the Bureau of Labor Statistics (BLS). Data were drawn from the monthly employment files maintained in electronic format by the BLS. Monthly estimates were summed over the year and then divided by 12. Zero estimates were considered valid estimates from the survey, therefore, even when an occupation did not occur in one or more months, the yearly sum was divided by 12. The annual employment estimates were based on workers' primary industry and occupation. Since these estimates do not account for hours worked, a person whose primary job is part-time is treated equally with a person who works full-time at their primary job. Additional information about the Current Population Survey can be found in *Employment and Earnings*, which is published monthly by the BLS.

Information on occupation and industry was coded according to the BOC classification systems. Data for 1990 and 1991 were coded according to the 1980 BOC classification system (BOC, 1982) and data for 1992 through 1994 were coded according to the 1990 BOC classification system (BOC, 1992). The 1980 BOC classification of occupation was converted to the 1990 BOC classification; for the current study results are presented using the 1990 BOC classification of occupation. The injury and employment data included in this study are for persons whose industry was coded as construction (BOC industry code = 60). Results are presented for the civilian work force only, because denominator data are not available for military personnel.

Annual fatality rates are presented as the number of deaths per 100,000 construction workers. Rates were calculated by gender, race, age-group, and cause of death. Occupation rates were calculated for those occupations that had ten or more deaths during the 5 years, while cause- and occupation-specific rates were calculated for those occupations that had 150 or more deaths during the 5 years. Confidence intervals (95% CI) for rates were calculated based on the standard errors of the employment estimates using the approximations and adjustments published in the *Employment and Earnings* (BLS, 1997). For each fatal-injury rate, the upper and lower bounds were calculated for the estimated number of employees used in the rate calculation. Then these upper and lower bounds were used to calculate rates above and below the initial fatal-injury rate.

Lifetime risk was calculated by using an equation proposed by the Occupational Safety and Health Administration (OSHA, 1995): $WLTR = (1 - (1 - R)^y) \times 1000$ where: WLTR = working lifetime risk; R = probability of a worker having a work-related fatal injury in a given year (*e.g.*, average annual fatal-injury rate); y = years of exposure to work-related injury; $(1 - R)^y$ = probability of surviving 'y' years without a work-related fatal injury ("y" set at 45 years); $1 - (1 - R)^y$ = probability of having a work-related fatal injury over 'y' years of employment. The variable WLTR is expressed as the number of deaths per 1000 workers over a 45-year working lifetime.

RESULTS

A total of 4661 work-related injury deaths were identified in the construction industry in the United States in 1990–1994, yielding an average annual rate of 12.7 deaths/100,000 construction workers. Table 1 presents the number of deaths and rates by age group. Rates were similar by age group until 44 years of age, increased slightly through age 55, then increased rapidly.

Within the construction industry, there were 38 occupations identified as having ten or more deaths during the 5 years, and among these, 22 had a rate higher than the average rate of 12.7/100,000 construction workers. Table 2 presents fatal-injury rates by occupation and year, and average annual rates by occupation for the 38 occupations that had ten or more deaths during the 5 years. Electrical power installers and repairers had the highest rate of 96.6, over seven times the average rate of 12.7; followed by structural metal workers (86.4); operating engineers (41.0); drillers, earth (34.8); and supervisors—painters, paperhangers, and plasterers (34.5). The largest number of injury deaths occurred to construction laborers (1,133 deaths), followed by carpenters (408 deaths), construction supervisors, n.e.c. (392 deaths), operating engineers (309 deaths), and electricians (261 deaths).

Overall, the number of fatal work-related injuries declined by 15%, from 1,077 deaths in 1990 to 920 deaths in 1994. The fatal-injury rates decreased by 12%, from 13.9 in 1990 to 12.3 in 1994. Among those occupations that had 150 deaths or more during the 5 years (1990 to 1994), truck drivers; operating engineers; construction supervisors; construction managers and administrators, n.e.c.; and electricians experienced a rate decrease greater than 12% over the 5 years. Construction laborers, the occupation that had the largest number of deaths in construction, experienced an 11% decrease in rate over the years. There was little change in the fatal-injury rate of the painter; carpenter; and construction trades, n.e.c. occupations. Rates for other occupations

Table 1. Work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994 by age-group.[a]

Age groups	Employees[b]	Deaths[c]	Rates[d]	95% CI[e]
16–19	1,080,794	97	9.0	8.2–9.8
20–24	3,763,658	428	11.4	10.6–12.3
25–29	5,280,123	627	11.9	11.2–12.7
30–34	6,379,550	693	10.9	10.3–11.5
35–39	5,733,686	666	11.6	10.9–12.4
40–44	4,602,280	534	11.7	10.8–12.5
45–49	3,303,197	457	13.8	12.8–15.1
50–54	2,661,078	369	13.9	12.7–15.3
55–59	2,018,620	317	15.7	14.2–17.5
60–64	1,195,374	233	19.5	17.2–22.6
65–69	429,425	110	25.6	20.9–33.2
70–74	184,906	75	40.6	30.1–62.1
75–79	52,302	36	68.8	41.7–196.6
80+	20,141	17	84.4	42.6–4548

[a] Two death certificates had unknown age.

[b] Employees: estimated number of employees for 1990 through 1994 from the Current Population Survey (CPS) microdata maintained by the Bureau of Labor Statistics.

[c] Deaths: Number of occupational injury deaths for 1990 through 1994 from the National Traumatic Occupational Fatalities Surveillance system maintained by the National Institute for Occupational Safety and Health.

[d] Rate: Number of occupational fatal injuries per 100,000 workers.

[e] Approximate 95% Confidence intervals are based on the standard errors for the employment estimates in the CPS as published in the *Employment and Earnings* (BLS, 1997).

(*e.g.*, structural metal workers) and for occupations that had fewer than 150 deaths fluctuated widely during the study period.

Table 3 presents cause-specific rates by year in construction. The four leading causes of death (falls, motor-vehicle incidents, electrocutions, and machine-incidents) account for two-thirds of the fatal injuries in construction. Though there was a general decline in the annual rates for these causes of death, the rates varied sufficiently by year to preclude assessment of this trend over such a short time period.

Table 2. **Work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994 by occupation and year.**

BOC code and occupations[a]		Average rate (1990–1994)			Rate by year					Change in rate[e]
		N[b]	R[c]	95% CI[d]	90	91	92	93	94	(%)
All	Construction industry	4661	12.7	12.6–12.8	13.9	12.5	12.6	12.1	12.3	–12.0
577	Electrical power									
	Installers and repairers	49	96.6	79.3–123.7	109.7	61.6	70.0	117.9	120.1	9.5
597	Structural metal workers	174	86.4	77.4–97.8	70.5	79.7	107.5	77.1	105.6	49.7
844	Operating engineers	309	41.0	38.7–43.7	50.8	44.4	38.0	36.9	35.0	–31.0
598	Drillers, earth	28	34.8	29.3–42.8	41.1	40.2	—[g]	28.1	57.1	39.0
556	Supervisors; painters	18	34.5	27.9–45.2	30.8	—[g]	—[g]	84.6	—[g]	
869	Construction laborers	1133	34.0	33.0–35.0	37.2	29.2	37.1	33.0	33.3	–10.4
643	Boilermakers	12	33.0	26.3–44.5	—[g]	—[g]	—[g]	—[g]	—[g]	
216	Engineering technicians[NEC f]	18	29.8	24.4–38.2	—[g]	68.7	42.4	—[g]	—[g]	
783	Welders and cutters	102	28.5	26.2–31.3	27.1	31.3	24.0	36.7	25.0	–7.7
544	Millwrights	16	27.1	22.2–34.8	28.1	—[g]	—[g]	—[g]	49.6	76.2
516	Heavy equipment mechanics	57	23.2	21.0–25.9	12.4	19.1	25.1	35.1	26.1	111.2
543	Elevator installers	16	22.5	18.9–27.5	26.4	35.2	—[g]	25.8	—[g]	
557	Supervisors; plumbers	11	22.3	17.9–29.5	—[g]	—[g]	—[g]	43.6	—[g]	
595	Roofers	209	21.5	20.4–22.6	16.3	27.2	19.7	16.5	29.7	82.9

849	Crane and tower operators	19	20.5	17.6–24.5	20.1	28.0	—[g]	24.6	—[g]	
804	Truck drivers	159	19.3	18.3–20.5	28.3	16.4	24.4	17.5	11.4	–59.7
856	Industrial truck/tractor equipment operator	17	17.2	14.8–20.6	25.3	—[g]	—[g]	25.2	—[g]	
653	Sheet metal workers	31	17.0	15.2–19.4	21.4	21.8	12.6	12.3	15.2	–29.0
005	Administrators and officials	11	17.0	14.0–21.6	—[g]	—[g]	—[g]	—[g]	—[g]	
599	Construction trades,[NEC]	114	17.0	16.0–18.1	18.0	23.4	12.3	14.4	17.1	–5.1
558	Construction supervisors,[NEC]	392	15.1	14.6–15.6	17.3	16.4	15.1	15.4	11.7	–32.2
575	Electricians	261	14.4	13.9–15.0	17.1	10.2	16.0	14.2	14.5	–15.1
555	Supervisors; electricians	13	12.0	10.4–14.4	—[g]	—[g]	—[g]	—[g]	—[g]	
593	Insulation workers	29	11.9	10.7–13.3	17.0	29.9	—[g]	—[g]	9.1	–46.4
035	Construction inspectors	10	10.2	8.7–12.2	—[g]	—[g]	—[g]	—[g]	—[g]	
053	Civil engineers	38	10.2	9.4–11.1	14.6	10.1	5.3	13.3	7.6	–48.0
563	Brickmasons	84	10.1	9.5–10.7	11.6	11.3	6.2	10.5	10.6	14
588	Concrete finishers	33	9.9	9.1–10.8	11.5	9.2	19.3	—[g]	9.8	–8.9
576	Electrician apprentices	11	9.8	8.5–11.7	—[g]	—[g]	—[g]	—[g]	18.8	154.0
853	Excavation machine operators	33	9.1	8.4–10.0	8.1	9.4	6.5	11.2	10.4	28.1
585	Plumbers/pipefitters	131	8.8	8.5–9.2	10.3	7.2	11.6	6.8	8.2	–21.2
567	Carpenters	408	7.6	7.4–7.8	7.3	6.6	8.7	7.6	7.9	7.3
579	Painters	159	7.4	7.1–7.7	8.0	7.7	6.2	7.5	7.5	–6.5
866	Helpers, construction trades	29	5.8	5.4–6.3	9.9	4.0	6.0	—[g]	5.2	–47.8
022	Managers/administration, NEC	226	5.2	5.1–5.4	5.9	5.4	5.4	5.1	4.4	–24.5
855	Grader/dozer/scraper operators	15	4.4	4.1–4.9	5.6	6.0	—[g]	—[g]	5.9	3.7

Table 2. Work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994 by occupation and year. (continued)

BOC code and occupations[a]	Average rate (1990–1994)			Rate by year					Change in rate[e]
	N[b]	R[c]	95% CI[d]	90	91	92	93	94	(%)
534 Heat/air condition mechanics	27	3.8	3.6–4.1	4.1	—[g]	5.2	5.5	2.8	–31.8
573 Drywall installers	17	2.6	2.4–2.7	3.4	—[g]	—[g]	3.1	3.9	15.2

[a] Occupational codes were based on the *1990 Census of Population:Alphabetic Index of Industries and Occupations* (BOC, 1992).

[b] N: Number of occupational injury deaths for 1990 through 1994 from the National Traumatic Occupational Fatalities surveilance system maintained by the National Istitute for Occupational Safety and Health.

[c] R: Rate = Number of occupational injury deaths per 100,000 workers. The estimated number of employees used in the rate calculations were from the Current Population Survey (CPS) microdata maintained by the Bureau of Labor Statistics.

[d] Approximate 95% Confidence intervals are based on the standard errors for the employment estimates in the CPS as published in the *Employment and Earnings* (BLS, 1997).

[e] Change in rate: The net change in rate over the period expressed as a percent of the rate in 1990 {Δ = ((1994 rate–1990 rate)/1990 rate) ×100}.

[f] NEC: Not elsewhere classified.

[g] Rates were not calculated when the number of deaths was ≤3.

Table 3. Cause-specific work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994 by year.

	1990		1991		1992		1993		1994		Change in rate[d]
Cause of death[a]	N[b]	R[c]	N	R	N	R	N	R	N	R	(%)
Falls	283	3.7	237	3.3	215	3.0	223	3.1	262	3.5	–4.6
Motor vehicle	206	2.7	138	1.9	177	2.5	181	2.5	162	2.2	–19.0
Electrocution	133	1.7	110	1.5	115	1.6	94	1.3	109	1.5	–16.0
Machine	131	1.7	119	1.7	100	1.4	118	1.6	94	1.3	–26.0
Struck by falling objects	82	1.1	69	1.0	63	0.9	60	0.8	53	0.7	–33.0
Suffocation	41	0.5	24	0.3	24	0.3	21	0.3	27	0.4	–32.0
Homicide	29	0.4	29	0.4	31	0.4	31	0.4	34	0.5	20.8
Explosion	26	0.3	25	0.4	16	0.2	14	0.2	23	0.3	–8.9
Struck by flying objects	27	0.3	14	0.2	21	0.3	19	0.3	19	0.3	–28.0
Nature/environment	28	0.4	27	0.4	28	0.4	30	0.4	38	0.5	–33.0
Drowning	20	0.3	11	0.2	11	0.2	11	0.2	13	0.2	–33.0
Fires	16	0.2	15	0.2	11	0.2	9	0.1	7	0.1	–55.0
Poisoning	15	0.2	8	0.1	11	0.2	6	0.1	21	0.3	44.2

Table 3. Cause-specific work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994 by year. (continued)

	1990		1991		1992		1993		1994		Change in rate[d]
Cause of death[a]	N[b]	R[c]	N	R	N	R	N	R	N	R	94–90 (%)
Suicide	14	0.2	16	0.2	12	0.2	20	0.3	15	0.2	10.4
Other incidents	11	0.1	35	0.5	34	0.5	33	0.5	28	0.4	162.0
Other transportation	11	0.1	12	0.2	7	0.2	11	0.2	12	0.2	12.7
Intent Unknown	4	0.1	2	0.0	3	0.0	3	0.0	3	0.0	–23.0

[a] Cause of Death: External cause-of-death (E-800 through E-999) from the *International Classification of Disease* (WHO, 1977).

[b] N: Number of occupational injury deaths for 1990 through 1994 from the National Traumatic Occupational Fatalities surveillance system maintained by the National Institute for Occupational Safety and Health.

[c] R: Rate = Number of occupational injury deaths per 100,000 workers. The estimated number of employees used in the rate calculations were from the Current Population Survey (CPS) microdata maintained by the Bureau of Labor Statistics.

[d] Change in rate: The net change in rate over the period expressed as a percent of the rate in 1990 {Δ=((1994 rate–1990 rate)/1990 rate) ×100}.

Table 4 presents cause- and occupation-specific rates and their associated working lifetime-risk estimates for occupations that had 150 or more deaths during the 5 years. The highest rate for falls occurred among structural metal workers (54.1/100,000 construction workers), more than 16 times the average rate of 3.3 for falls in construction, followed by roofers (14.7) and construction laborers (7.4). The highest rate for motor-vehicle incidents occurred among truck drivers (12.3), five times the average of 2.4 for motor-vehicle-related incidents in construction, followed by operating engineers (10.1) and construction laborers (8.0). The highest rate for machinery incidents occurred among operating engineers (15.5), 10 times the average of 1.5 for machinery incidents in construction, followed by structural metal workers (7.9) and construction laborers (3.8). The highest rate for electrocution occurred among electricians (6.6), more than four times the average of 1.4 for electrocution in construction, followed by structural metal workers (4.5) and construction laborers (3.1). Ten cause- and occupation-specific combinations in Table 4, have working lifetime risks equal to or exceeding 3 deaths per 1,000 working lifetimes. The highest working lifetime risks are for falls among structural metal workers (24.1), machinery incidents among operating engineers (7.0), falls among roofers (6.6), and motor-vehicle incidents among truck drivers (5.5) and operating engineers (4.5).

State-specific fatal work-related-injury rates are provided in Table 5. The District of Columbia, Wyoming, Alaska, West Virginia, North Dakota, and South Carolina had the highest rate over the 5-year period. Most of the Mountain, Central and Southern states had rates above the national average. The lowest rates were found in the northeast and the States of Arizona, Ohio, Washington, Michigan and California.

DISCUSSION

This study has reviewed work-related fatal injuries to all occupations within the construction industry and is the first report providing a comprehensive national profile of work-related fatal injuries in the construction industry by occupation and cause of death in the United States. Pollack *et al.* (1996) published work-related fatality rates in construction for selected occupations or occupation groups using 1992 to 1993 CFOI data and CPS data. They used full-time equivalent workers as a denominator to calculate rates, which takes hours-worked into consideration when estimating exposure (Pollack *et al.*, 1996; Ruser, 1998). In spite of differences in data sources used to identify work-related fatalities and the definition of the denominator, results from our study closely agreed with Pollack's study. But some high-risk occupations were identified in our study that were not identified in their study, such as construction supervisors; truck drivers; engineering technicians; boilermakers; earth drillers; welders and cutters; elevator installers; and heavy-equipment mechanics. Pollack *et al.* (1996) grouped electricians with electrical-power installers and repairers, an occupation that, in this study, had a fatality rate more than six times the rate for electricians.

Table 4. Occupation- and cause-specific work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994.

Occupations[b]	Falls		Motor Vehicle		Machinery		Electrocution		Struck by Falling objects	
	R[c]	WLTR[d]	R	WLTR	R	WLTR	R	WLTR	R	WLTR
All Occupations	3.3	1.5	2.4	1.1	1.5	0.7	1.4	0.7	0.9	0.4
Structural metal workers	54.1	24.1	1.5	0.7	7.9	3.6	4.5	2.0	7.4	3.3
Operating engineers	1.5	0.7	10.1	4.5	15.5	7.0	1.6	0.7	3.9	1.7
Construction Laborers	7.4	3.3	8.0	3.6	3.8	1.7	3.1	1.4	3.2	1.4
Roofers	14.7	6.6	1.5	0.7	0.4	0.2	2.0	0.9	0.1	0.0
Truck drivers	0.4	0.2	12.3	5.5	2.1	0.9	1.0	0.4	1.1	0.5
Electricians	3.1	1.4	1.2	0.5	1.0	0.4	6.6	3.0	0.2	0.1
Construction Supervisors	4.0	1.8	3.4	1.5	1.6	0.7	1.6	0.7	0.8	0.4
Carpenters	3.2	1.5	0.6	0.3	0.5	0.2	0.8	0.3	0.7	0.3
Painter	3.7	1.7	0.5	0.2	0.2	0.1	1.0	0.5	0.2	0.1
Managers and administrators	1.2	0.5	1.0	0.4	0.7	0.3	0.5	0.2	0.2	0.1

[a] Cause of Death: External cause-of-death (E-800 through E-999) from the International Classification of Disease (WHO, 1977).

[b] Occupational codes were based on the 1990 Census of Population: Alphabetic Index of Industries and Occupations (BOC, 1992).

[c] R: Rate = Number of occupational injury deaths per 100,000 workers. The estimated number of employees fused in the rate calculations were from the Current Population Survey (CPS) microdata maintained by the Bureau of Labor Statistics.

[d] WLTR: Working lifetime risk expressed as the number of occupational injury deaths per 1000 workers over a 45-year working lifetime.

Table 5. State-specific work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994.

State	Employees[a]	Deaths[b]	Rates[c]	95 % CI[d]
District of Columbia	32,337	15	46.4	32.1 – 83.5
Wyoming	63,554	25	39.3	30.3 – 56.0
Alaska	66,895	24	35.9	27.9 – 50.2
West Virginia	173,918	50	28.7	24.3 – 35.3
North Dakota	68,026	19	27.9	21.8 – 39.0
South Carolina	438,549	120	27.4	24.6 – 30.9
Utah	202,010	50	24.8	21.3 – 29.6
Mississippi	312,825	73	23.3	20.6 – 26.9
Montana	105,048	24	22.8	18.6 – 29.6
South Dakota	79,620	18	22.6	17.9 – 30.6
Georgia	774,444	174	22.5	20.7 – 24.5
Kansas	283,846	63	22.2	19.5 – 25.8
New Mexico	203,051	45	22.2	19.0 – 26.5
Nebraska	183,353	39	21.3	18.1 – 25.8
Illinois	1,169,535	247	21.1	19.8 – 22.7
Texas	2,220,012	466	21.0	20.0 – 22.1
Arkansas	280,825	58	20.7	18.1 – 24.0
Louisiana	552,542	113	20.5	18.6 – 22.8
Alabama	526,449	107	20.3	18.4 – 22.6
Iowa	334,254	66	19.7	17.5 – 22.6
Idaho	158,515	31	19.6	16.5 – 24.0
Florida	1,743,166	332	19.0	18.0 – 20.2
Pennsylvania	1,296,323	231	17.8	16.7 – 19.1
Nevada	213,332	38	17.8	15.3 – 21.3
Missouri	603,019	107	17.7	16.2 – 19.6
North Carolina	864,982	144	16.6	15.4 – 18.1
Kentucky	431,633	71	16.4	14.8 – 18.5
Colorado	445,907	73	16.4	14.7 – 18.4
New York	1,680,163	261	15.5	14.7 – 16.5
Indiana	642,579	99	15.4	14.1 – 17.0
Tennessee	573,032	84	14.7	13.3 – 16.3
Oregon	370,517	53	14.3	12.8 – 16.3
New Jersey	793,096	111	14.0	12.9 – 15.3
Rhode Island	100,518	14	13.9	11.2 – 18.4

Table 5. State-specific work-related fatal-injury rates among U.S. construction workers who died from 1990 to 1994. (continued)

State	Employees[a]	Deaths[b]	Rates[c]	95 % CI[d]
Virginia	893,809	119	13.3	12.3 – 14.5
Oklahoma	319,066	42	13.2	11.6 – 15.2
Hawaii	184,715	24	13.0	11.1 – 15.7
Wisconsin	605,241	74	12.2	11.2 – 13.5
Minnesota	482,781	59	12.2	11.0 – 13.7
California	3,255,412	388	11.9	11.4 – 12.4
Michigan	901,828	107	11.9	11.0 – 12.9
Massachusetts	584,928	68	11.6	10.6 – 12.9
New Hampshire	140,650	16	11.4	9.5 – 14.3
Washington	680,334	71	10.4	9.6 – 11.5
Ohio	1,102,510	112	10.2	9.5 – 10.9
Maine	156,838	14	8.9	7.5 – 11.1
Delaware	103,336	9	8.7	7.1 – 11.3
Maryland	670,555	53	7.9	7.2 – 8.7
Arizona	478,392	33	6.9	6.2 – 7.7
Connecticut	335,084	22	6.6	5.8 – 7.6
Vermont	86,027	5	5.8	4.6 – 7.9

[a] Employees: estimated number of employees for 1990 through 1994 from the Current Population Survey (CPS) microdata maintained by the Bureau of Labor Statistics.

[b] Deaths: Number of occupational injury deaths for 1990 through 1994 from the National Traumatic Occupational Fatalities Surveillance system maintained by the National Institute for Occupational Safety and Health.

[c] Rate: Number of occupational fatal injury deaths per 100,000 workers.

[d] Approximate 95% Confidence intervals are based on the standard errors for the employment estimates in the CPS as published in the *Employment and Earnings* (BLS, 1997).

A previous study of work-related fatal injury among construction workers using NTOF data for the period of 1980 to 1989 (Kisner and Fosbroke, 1994) reported a rate of 21.7/100,000 workers in the construction industry in 1989, a rate that is nearly twice the average annual rate of 12.7/100,000 in this study. The reason for the difference in the fatal-injury rates between the two studies is the fact that the denominator used in Kisner and Fosbroke's study was obtained from the County Business Patterns, an establishment-based employment count developed by the Bureau of the Census, which does not include owner-operators. These excluded owner-operators make up a significant proportion of the construction industry. Kisner and Fosbroke (1994) reported fatality rates by occupation division and found that laborers had the highest rate of 39.5 in construction. The occupational divisions used in their study are not comparable to the detailed occupations used in this study, so laborers in their study are not comparable to construction laborers in this study.

Among the 38 occupations identified to have ten or more deaths during the 5 years, 33 are blue collar occupations (BOC occupational codes = 503 – 889). The 22 occupations identified as having a fatal-injury rate greater than the U.S. construction industry average, accounted for 35% of the industry's employment. However, deaths from these 22 occupations accounted for 68% of all work-related injury deaths in construction. The average rate for these 22 occupations is 24.9, while the rate in all of construction is 12.7. The ranking of occupations by fatal injuries should be used in setting research, regulatory, and prevention priorities for the construction industry. Setting such priorities requires consideration of the number of injuries (which provides a measure of the magnitude of the injury problem for an occupation) and the rate of injury (which provides a measure of injury risk for an occupation).

Special-trade occupations usually had a high incidence of work-related fatal injuries related to one or two specific causes of death. For example, electricians, and electrical power installers and repairers had a high injury rate of electrocution; truck drivers had a high rate of motor-vehicle- related deaths; and roofers had a high rate of fatal falls. In contrast, construction laborers experienced elevated risks for all causes of death, with the exception of death from air-transport-related incidents (results for other causes of death are not presented due to space constraints). The mortality patterns by occupation and cause of death presented in Table 4 should be useful for developing occupation-specific prevention programs. For example, a prevention program for structural-metal workers should focus on deaths from falls, machinery incidents, and electrocutions; and a prevention program for operating engineers should focus on deaths from machinery and motor-vehicle incidents. In contrast, a prevention program for construction laborers should cover a broad range of safety hazards.

Construction workers aged 30 to 34 years had the lowest fatality rates, while workers in the older age groups had the highest rates. Other studies have also found a higher risk of fatal injury among older construction workers (Buskin and Paulozzi, 1987; Kisner and Fosbroke, 1994; Kisner and Pratt, 1997). Warr (1993, 1994) discussed age-impairment as related to both age-related shortcomings and experience. While the relationship identified in this study between fatal injuries and age among construction workers may suggest that lack of experience among younger construction workers (20 to 29 years old) and age-related shortcomings among older construction workers (45 years or older) may be important risk factors, information on such age-related factors is not available in NTOF. Injury severity and age-related complications have also been cited as factors contributing to the high fatal-injury rates among older workers (Kisner and Pratt, 1997; Personic and Windau, 1995). Though older workers have high fatal-injury rates, they have low OSHA recordable injury rates, suggesting that when injured, older workers may have more serious outcomes (Personick and Windau, 1995). In their paper on fatalities among older workers, Kisner and Pratt (1997) provide a good review of the literature on the relationship between age and fatal-injury rates.

The construction industry in general experienced a decline in work-related fatal-injury rate over the years of 1980 to 1989 (Stout, Jenkins, and Pizatella, 1996). This decline continued into the 1990's. However, the decline of the fatality rate did not occur equally across occupations and causes of death over the period from 1990 to 1994. The causes of death and the occupations that had a rate decline may be indicative of the effectiveness of recent regulatory changes, current prevention programs, or other positive changes in working practices or environments. The causes of death and the occupations that had little change in fatality rates may indicate a need for improvement of current working practices or environments.

NIOSH has reported that the construction industry accounted for the largest number of work-related-injury deaths in 19 states and was the highest risk industry in three states (CDC, 1998). The geographic variation in fatal injuries in construction presented in Table 5 generates questions for future research. Potential factors that might contribute to this geographic variation are geographic differences in the type of construction, the type of equipment used, weather and economic conditions, union and population density, pre-hospital care availability, workforce experience, and implementation of safety and health programs. Unfortunately, information on these risk factors is not available in NTOF data. The states with the highest construction-fatality rates should clearly be the focus of enhanced injury-prevention efforts.

Fosbroke *et al.* (1997) recently applied the concept of working lifetime risk to fatal occupational injury studies, which facilitates the comparison of occupational injury risks with risk assessments for occupational disease. They suggested that risk assessments for occupational injuries and occupational illnesses should be considered equally with each other (Fosbroke *et al.*, 1997). The industry-wide (all occupations in construction combined) working lifetime-risk estimates for the five leading causes of death ranged from 0.4 to 1.4 in 1000 working lifetimes (Table 4), levels that are below, or near, the one death in 1,000 working lifetimes that OSHA uses as an indicator of significant hazard. However, for each of these five causes of death, there are specific subgroups of construction workers who face considerably higher working lifetime risks of fatal injury on the job. Ten occupation-by-cause-of-death combinations had lifetime risk estimates of at least 3 times OSHA's measure of significant hazard (Table 4). Another ten combinations had lifetime-risk estimates between 1.4 and 2.0 times greater than OSHA's measure of significant hazard. While regulatory action is underway with respect to some of these injury exposures (*e.g.*, falls among structural metal workers is an emphasis of the negotiated rulemaking on steel erection), other injury hazards (*e.g.*, motor-vehicle risk to operating engineers and construction laborers) are not covered by specific OSHA construction standards.

LIMITATIONS

Many authors have reviewed the limitations of using death certificates in general and NTOF data in particular for the study of fatal occupational injury. These limitations should be kept in mind when interpreting the results of this study. Of particular concern is the use of usual industry and usual occupation, rather than the industry and occupation at the time of injury (Steenland and Beaumont, 1984) and the accuracy of the injury-at-work item on death certificates (Russell and Conroy, 1991). The result of these limitations is that some worker populations and causes of death are underrepresented in occupational studies based on death certificates. Even with the limitations of death certificates and NTOF for studies such as this, death certificates are the single document source that capture the greatest proportion of work-related fatal injuries, approximately 80% (Stout and Bell, 1991), and the NTOF surveillance system provides the most detailed data on fatal occupational fatalities during the study period, 1990 to 1994.

In 1992, the Bureau of Labor Statistics introduced the Census of Fatal Occupational Injuries (CFOI). Though CFOI provides a more comprehensive capture of work-related injury than NTOF (due to its multiple source documents), results from CFOI should be similar to results from NTOF because approximately 80% of the cases in CFOI have a death certificate as one of the source documents (Drudi, 1995). However, differences in the way the cause of death is classified would yield slightly different results, because CFOI uses the event or exposure leading to injury or illness as defined in the Occupational Injury and Illness Classification System (OIICS) (ANSI, 1995) rather than the cause of death as defined in the International Classification of Diseases-Ninth Revision (WHO 1977). This study builds on the literature developed from NTOF throughout the 1980s and early 1990s, using the same cause-of-death classification system used by these earlier studies. Another limitation of this study is that results for certain occupation categories in this study should be interpreted with caution because of the small number of deaths. To obtain reliable fatal-injury rates and lifetime-risk estimates for occupations with a small annual number of deaths, continual data collection over a number of years is essential. An alternative might be to group these occupational categories; however, work needs to be done to determine occupational groupings which are logical in terms of injury prevention.

The WLTR estimates provided in this paper represent an average risk to fatal injuries of the construction population, expressed as the number of deaths per 1000 working lifetimes. Though the equation presumes working lifetime of 45 years, the rate estimates used in the WLTR equation was not limited to workers of specific ages (*e.g.*, workers less than 20 years old and older than 65 years old are include in the calculation of R). The WLTR equation is simplistic—it is not intended to predict the actual risk of an individual who works at a given occupation for 45 years. In fact, the equation assumes that exposures to fatal injuries, though unknown, are constant over time. Any future changes in risk are not accounted for by the equation. In this paper, the average annual rate from 1990 through 1994 was used as an estimate of the fatal injury risk experienced in the construction industry and this risk estimate was assumed to be constant over time. This multi-year average limits the effect of year-to-year variations in fatal-injury rates on the resulting working lifetime risk estimates.

The WLTR equation does not change rankings developed using fatal injury rates. WLTR estimates are calculated because they can be expressed in a manner that is comparable to lifetime risk estimates previously developed for occupational illnesses, something that annual injury rates cannot be used for. Though a WLTR estimate can be calculated whenever a rate is calculated, to be meaningful, the WLTR estimate should be calculated for a specific cause of injury for a specific population. For example, it is appropriate to compare electrocution among carpenters with lung cancer among uranium miners, but it is not appropriate to compare all fatal injuries among carpenters to lung cancer among miners. Therefore, WLTR estimates were not provided for univariate variables, such as age, occupation, state, and cause of death.

CONCLUSIONS

Although construction has experienced a decline in its fatal-injury rate since 1980, it remains one of the most dangerous industries in the United States: on average, 2.6 construction workers were killed from on-the-job injury every day in the United States during the years of 1990 to 1994. The severity of the fatal-injury problem in this industry is clearly described in the National Occupational Research Agenda (NORA) document (NIOSH, 1996). The NORA document calls for moving the Nation's research effort from the broad generalities of national burden of disease and injury, to the specifics of targeted-intervention programs. The findings of this paper support the call for targeted, specific research by defining fatal-injury risk for specific occupations and causes of death within the high-risk construction industry, identifying differences in state-specific construction-injury rates, and demonstrating variability in fatal-injury risks and patterns of fatal injury across occupations within the construction industry. The study's results indicate where improvements in working practices and environments in the construction industry are urgently needed and can be used to tailor occupation-specific injury prevention programs.

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Robbery-Related Injury in Convenience Stores: Estimating Lifetime Risk and Identifying High-Risk Populations

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ABSTRACT

Robbery-related injuries constitute a major risk for convenience store workers in the United States. Studies that focus on the injury outcomes associated with convenience store robbery are extremely limited in number. This is a prospective study of 1271 convenience stores in three metropolitan areas of Virginia between February 1, 1995 and September 30, 1996. The study quantifies the lifetime risk for an occupational robbery-related injury occurrence and determines the relative importance of various types of factors in the classification of high risk stores. Lifetime risk was estimated by calculating the probability in convenience stores for having one or more employee(s) sustain at least one robbery-related injury over a range of years that a store could be in operation. Results indicate that knowledge of the circumstances of the robbery are needed to maximize the identification of high risk stores. Estimated lifetime risk reaches 567 stores with an occupational robbery-related injury occurrence per 1,000 stores in operation after 45 years. This study addresses limitations of previous research by including information on clerk resistance and the number of robbers in its analysis. These two circumstantial characteristics of robbery have been previously hypothesized to be associated with robbery-related injury.

Key Words: resistance, classification, occupational and risk assessment.

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INTRODUCTION

Robbery-related injuries constitute a major risk for convenience store workers in the United States. In 1990, reports show that the convenience store industry experienced between 23,000 and 38,000 robberies (Schreiber, 1991). This research suggests that potentially tens of thousands of convenience store workers are directly placed at risk for robbery-related injuries each year. Based on survey responses of the National Association of Convenience Stores (NACS) member companies, approximately 1 out of every 5 convenience stores in the United States is robbed each year (Schreiber, 1991). In a study of 1835 convenience store robberies across selected metropolitan areas in seven eastern states in the U.S., Amandus et al. (1997) demonstrated that approximately 1 out of every 8 robberies was associated with an injury to at least 1 employee and 2 out of every 100 robberies were associated with a severe injury to at least 1 employee. Schreiber (1991) reported that homicide incidence rates in convenience stores were 1 incident per 953 stores in 1989 and 1 per 731 stores in 1990. Sexual assault incidence rates were reported as 1 incident per 472 stores in 1989 and 1 incident per 401 stores in 1990. Other violent crime (excludes homicide, robbery, and sexual assault) incident rates, including assault, abduction, and intentional injuries were 1 incident per 61 stores in 1989, and 1 incident per 46 stores in 1990. Although homicides and rapes in convenience stores are not always associated with robbery, Erickson (1991) showed that approximately two-thirds of homicides and one-third of rapes are robbery related. These results imply that thousands of convenience store workers sustain robbery-related injuries and hundreds of convenience store workers sustain severe robbery-related injuries each year.

Numerous studies have evaluated risk factors for convenience store robbery (Hunter, 1988; Amandus *et al.*, 1995; Hunter and Jeffery, 1991). Such studies have consistently indicated that the store's environmental designs (*e.g.*, escape routes, lighting, visibility, and other factors) affect the probability of robbery. Characteristics of the surrounding environment and population (*e.g.*, the degree of social disorganization, presence of gasoline service, and the amount of vehicular traffic) have also been identified as significantly associated with robbery occurrence (Duffala, 1976; D'Alessio and Stolzenberg, 1990). However, these studies only address factors associated with convenience store robbery. Conclusions concerning risk for occupational injury, based on these studies, require the assumption that inferences based on risk for robbery also hold for robbery-related injury. While recommendations for robbery interventions are designed to lower a convenience store's risk for robbery, their relative effectiveness in reducing a convenience store's risk of robbery-related injury is unclear. Until there exists conclusive research showing which factors protect against robbery-related injuries or until robbery interventions are proven overwhelmingly successful such that robbery no longer occurs in convenience stores, fewer robberies may not necessarily imply fewer violent robberies.

Studies that focus on the injury outcomes associated with convenience store robbery are extremely limited in number. Previous studies of selected metropolitan areas have evaluated risk factors for injury conditional on robbery and provided annual estimates for injury conditional on robbery, but did not address the overall probability of robbery-related injury (Amandus *et al.*, 1996; Amandus *et al.*, 1997). The purpose of this study is to estimate the lifetime risk for an occupational robbery-related injury occurrence in convenience stores and to determine the relative importance of various types of factors in the classification of high-risk stores.

METHODS

The dynamic study population included all convenience stores, N = 1271, in the Virginia Commonwealth from the following counties and cities: Arlington County, Alexandria, Chesapeake, Chesterfield County, Fairfax County, Hampton, Henrico County, Newport News, Norfolk, Portsmouth, Prince William County, Richmond, Suffolk, and Virginia Beach. All convenience store robberies, including those reoccurring in the same convenience store, were prospectively identified through police reports between February 1, 1995 and September 30, 1996. Data collected included staff and store characteristics, distance to various police focal points for criminal activity, and the circumstances of the robbery. Data concerning the occurrence and circumstances of robbery were abstracted from police reports by the Virginia Department of Criminal Justice Services. Examples of the circumstantial information include: number of robbers, type of weapon used, time of the robbery, clerk resistance, and injury status. Trained interviewers administered clerk and manager questionnaires and completed store evaluation forms. Clerks provided information on the following staff and store characteristics: the number of clerks on duty, presence of cash limit policies, employee demographics including age, gender, and race, permission to use a weapon in the event of robbery, whether weapons have been kept in the store during the previous year, whether a weapon was being kept on the premises, and whether they had received training in robbery prevention. Clerks also provided circumstantial information, including whether customers were present in the store during the robbery and information on the amount of money that was stolen. Managers provided information on staff characteristics, including their date of birth, gender, and race. Managers also provided the following store information: store name and address, size of the company, store type (e.g. corporate, franchise, independent or dealer), store age, and the store size. Retired police officers completed store evaluations, determining the presence of cash limit signs, drop safes, bullet resistant shields and video security systems. They also noted whether the drop safe was visible and whether the security system included a video monitor that could be seen by customers and robbers. Information on the surrounding area was also collected. This data included the distance (in miles) between the store and the following focal points for high crime activity: known drug trafficking activity, loitering youth and gangs, subsidized public housing projects, privately owned multifamily dwellings, and areas with broken windows, graffiti, and abandoned cars on empty lots. Census data provided information on the surrounding population of each store. Each store was assigned longitudinal and latitudinal coordinates according to its address. Then each store was matched with 1990 census-tract data. Although all the stores in the study participated, one store chain representing 39% of the robbed stores did not allow interviewers to administer questionnaires to their clerks. Instead, the company provided information on their cash handling policies, number of clerks on duty, demographics of employees, and the details on the circumstances of the robbery.

Robberies in the convenience stores were defined as any taking or attempt of taking goods or money from the store that involved the "threat of" or the "use of" force. An occupational robbery-related injury occurrence was defined as an event in which a store has one or more employee(s) sustain at least one robbery-related injury. Robbery-related injuries included all injuries sustained by employees from acts of intimidation or physical assault experienced during the robbery. The injuries varied in their degree of severity and were both fatal and nonfatal. Injuries ranged from bruises and scratches to traumatic stress, cuts, gunshots, and other types of wounds resulting from being struck. Severe injuries were defined as those injuries that required any medical treatment, prohibited the employee from returning to work, or resulted in death. Cases that required medical treatment included injuries that resulted from either being struck on the head with a blunt object (such as a baseball bat or bottle), being punched in the face, being shot on the side of the neck with a gun, getting sprayed in the face with pepper gas, or being cut on the hand with a knife.

Store populations at high risk for having an occupational injury during robbery were identified using logistic regression. Risk for injury conditional on robbery were modeled using data from all the robberies that occurred during the 20-month period. Classification results, including percent correctly classified, sensitivity, and specificity, were examined using a range of predicted probabilities as the cutoff value for high risk. Based on classification accuracy, sensitivity, and specificity for a range of predicted probabilities, robbery occurrences with a predicted probability of injury greater than 0.1 were classified as high risk. Potential risk factors for injury occurrence during robbery were grouped into three levels of data: (1) population and surrounding area characteristics, (2) staff and store characteristics, and (3) robbery circumstances. The number of variables that could be evaluated at each level needed to be restricted because there were only a small number of outcomes in which a robbery resulted in an occupational injury occurrence. Variables that were eligible for entry into the model selection process included those with a p-value less than or equal to 0.20 at the univariate level. The final model for each of the three levels of data included those variables listed in Table 1. These variables were chosen using a backward-selection procedure in logistic regression. Further details of the selection methods will be discussed elsewhere in a manuscript currently being written for the purposes of risk factor identification. Classification results were calculated using five different models: (1) population and surrounding area characteristics alone, (2) staff and store

Table 1. Predictors of occupational injury given robbery.

1. Characteristics of the surrounding store population and store area	A. High percent of population 15 to 24 years old
	B. Low per capita income
	C. High percentage of vacant buildings
	D. Close proximity to graffiti, broken windows, and abandoned cars on empty lots
2. Characteristics of the store procedures and staff demographics	A. Cash limit policy
	B. Younger age of manager
3. Characteristics specific to the circumstances of the robbery	A. Resistance of clerk during robbery
	B. Robber's type of force/weapon used
	C. Time of the crime
	D. Number of robbers

characteristics alone, (3) staff and store characteristics in addition to population and surrounding area characteristics, (4) robbery circumstances alone, and (5) robbery circumstances in addition to population and surrounding area and staff and store characteristics. These results were used to assess the level of detail needed to accurately identify stores at high risk for occupational injury during robbery.

Health hazards associated with working in a particular environment can accumulate over many years of exposure. Otherwise known as working lifetime risk (WLTR), these cumulative estimates of risk over time are useful in setting priorities for developing interventions in a particular industry. Although traditionally evaluated at the worker level, the WLTR formula was utilized in this study in order to quantify the store-level risk in the convenience store industry over a range of years that a store could be in operation. The risk for having an occupational robbery-related injury occurrence in convenience stores was assessed by calculating the lifetime risk (LR) using the following equation (Fosbroke, Kisner, and Myers, 1997).

$$LR = \left[1 - (1 - R)^{y}\right] * 1000$$

This study presents only point estimates of risk. 'R' represents the average annual risk for having an occupational robbery-related injury occurrence; '1-R' is the average annual risk of a store not having an occupational robbery-related injury occurrence, and 'y' represents the number of years that a store could be exposed to having an occupational robbery-related injury occurrence. The lifetime risk represents the average risk in convenience stores for having an occupational robbery-related injury occurrence over 'y' years of operation.

The lifetime risk formula assumes that R, the average annual probability in convenience stores for having an occupational robbery-related injury occurrence, remains constant over the years that a store is in operation. This formula also assumes that exposure to having a robbery-related injury occurrence remains constant over the years that a store is in operation. Lifetime risk presents an average risk among convenience stores, even though the risk may vary between individual stores. In this study, y was set from 6 months to 45 years, covering a long range of possible exposures. An individual employee's lifetime risk could not be estimated since the total number of clerks at risk was unknown.

R (in the life time risk formula) was estimated using the following formula:

$$R = \text{Probability}(\text{Injury } \{\text{year}\}) = \{1 - [1 - \text{Probability}(\text{Injury } \{\text{day}\})]^{365}\}$$

The Probability (Injury {day}) represents the average daily probability of having an occupational robbery-related injury occurrence. The Probability (Injury {year}) represents the average annual probability of having an occupational robbery-related injury occurrence. The Probability (Injury {day}) was estimated using the formula.

Probability(Injury {day}) = Probability(Injury|Robbery)*Probability(Robbery {day})

The Probability(Robbery {day}) represents the average daily probability of robbery. The Probability(Injury|Robbery) represents the conditional probability of injury given robbery, which was calculated as the number of occupational robbery-related injury occurrences divided by the total number of robberies.

Since annual risks may vary between individual stores, separate calculations of lifetime risk for subsets of the population were made. A range of the predicted probabilities of injury conditional on robbery were determined using the logistic model which included store and staff characteristics, population and surrounding area variables, and circumstances of the robbery. To quantify the effect of the variability in these predicted values on the annual probability of injury, the extreme values for predicted probability of injury conditional on robbery were also used to estimate lifetime risk.

RESULTS

Four hundred and sixty convenience store robberies were identified among the dynamic study population of 1271 convenience stores during the 20 month study period. These 460 robberies occurred in 299 of the convenience stores, or 24% of the total study population. Seven percent, N = 94, of all the convenience stores in the study population represent 55% of all the robbery events because these stores were robbed repeatedly, between two and seven times. Sixteen percent, N = 205, of all the convenience stores in the study population were robbed only once and represent 45% of all robbery events. Forty-one of the 460 robberies resulted in an occupational robbery-related injury occurrence, yielding a 0.089 probability of injury given robbery. Ten of the 460 robberies resulted in a severe occurrence of occupational robbery-related injury, yielding a 0.022 probability of severe injury given robbery.

Results concerning the identification of high-risk stores are listed in Table 2. Classification accuracy ranged between 63.2 and 80.8%, depending on which model was used. Model sensitivity ranged between 50.0 and 71.8%, while specificity ranged between 63.5 and 82.6%. The models which included circumstantial variables led to the highest classification percentage, the highest sensitivity and specificity, and the lowest percentages of false negatives and false positives. The remaining models achieved comparable results in terms of each of these statistics. False positives rates for all models were very high (between 72.4 and 86.7%), while false negative rates were very low (between 3.3 and 7.3%). The models were also rerun with the deletion of all observations with missing values for any variable in the model. Results were nearly identical. Details on the significant predictors for robbery-related injury will be discussed elsewhere in a manuscript currently being written for the purposes of risk factor identification.

Table 2. Classification: high risk robberies for occupational injury.

Model	No. Injuries	N	Accuracy	Sens	Spec	FPR	FNR
1. Population and surrounding area	36	380	64.5	50.0	66.0	86.7	7.3
2. Store and Staff[a]	35	375	63.2	60.0	63.5	85.5	6.1
store and staff[b]	34	358	70.9	50.0	73.1	83.7	6.7
3. Circumstances[a]	39	442	79.2	71.8	79.9	74.3	3.3
Circumstances[c]	33	349	80.8	63.6	82.6	72.4	4.4

Note: FPR = False-positive rate.
FNR = False-negative rate.

[a] Model includes only those characteristics indicated.

[b] Model includes characteristics of population and surrounding area characteristics.

[c] Model includes characteristics of store and staff and population and surrounding area.

The daily probability of robbery and the daily probability of occupational robbery-related injury occurrence were calculated as approximately 0.00057 and 0.00005, respectively. Assuming the average risk remains constant across time, the annual probability for having an occupational robbery-related injury occurrence was calculated as approximately 0.018. The logistic model was used to calculate the range of predicted probabilities for injury conditional on robbery using the 460 robbery events. Results varied between 0.005 and 0.874. These results were used to calculate a range of predicted probabilities for occupational robbery-related injury occurrence over the course of a year. The results of the annual risk for occupational robbery- related injury occurrence varied between 0.001 and 0.166.

Using the estimated annual probability for occupational robbery-related injury occurrence of 0.018, lifetime risk was calculated for a convenience store operating over a range of 6 months to 45 years. Additionally, lifetime risk was calculated with consideration for the variability in predicted probabilities of injury conditional on robbery, using the minimum and maximum risk estimates of 0.001 and 0.166, respectively. In order that lifetime risk might be clearly displayed for both small increments over the first 5 years, and for larger increments over the next 45 years, separate graphs were created for each interval. Figure 1 illustrates that empirical lifetime risk ranges between 9 and 80 stores with an occupational robbery-related injury occurrence per 1000 stores over 6 months to 4.5 years of store operation. Figure 2 illustrates that empirical lifetime risk reaches 567 stores with an occupational robbery-related injury occurrence per 1000 stores over 45 years of store operation. These

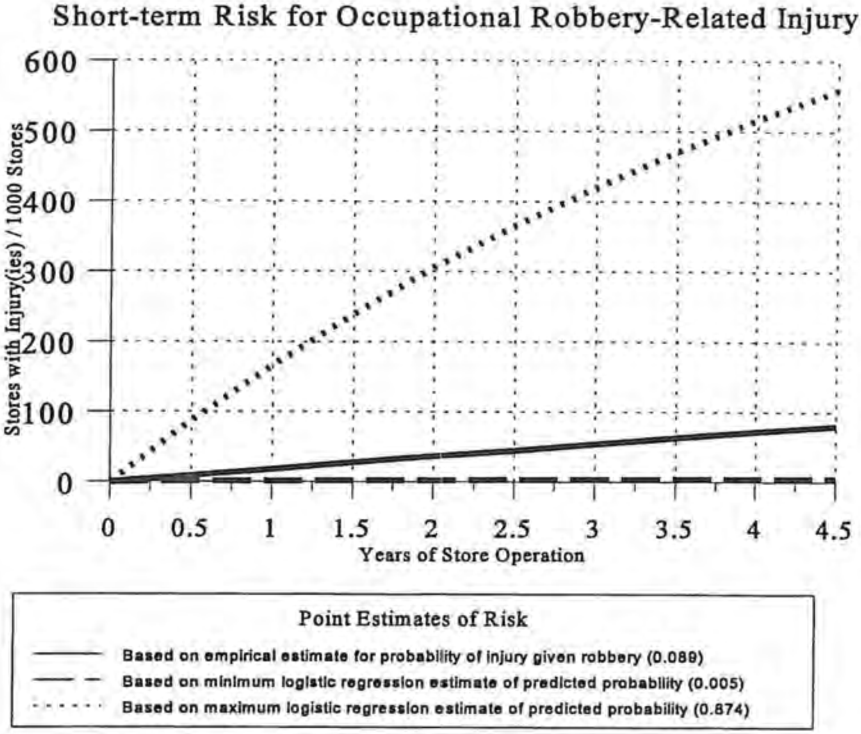

Figure 1. Lifetime risk in convenience stores for having an occupational robbery-related injury occurrence in which one or more employee(s) sustain at least one injury.

figures also show the lifetime risk using the minimum and maximum predicted probabilities. Figure 1 illustrates that lifetime risk for occupational robbery-related injury occurrences ranges between 1 and 5 per 1000 stores using the minimum predicted probability of injury conditional on robbery, and between 87 and 559 per 1000 stores using the maximum predicted probability of injury conditional on robbery. Figure 2 illustrates that lifetime risk for occupational robbery-related injury occurrences ranges between 5 and 48 per 1000 stores using the minimum predicted probability of injury conditional on robbery, and between 597 and 1000 per 1000 stores using the maximum predicted probability of injury conditional on robbery. Lifetime risk, based on the empirical risk estimate, shows the average risk of this population of convenience stores over a range of years that a store could be in operation. The estimates for lifetime risk, based on the minimum predicted probability, are representative of a subset of robbed stores in the population which had covariate values corresponding to the lowest prediction of injury risk given robbery. The lifetime risk estimated from the maximum predicted

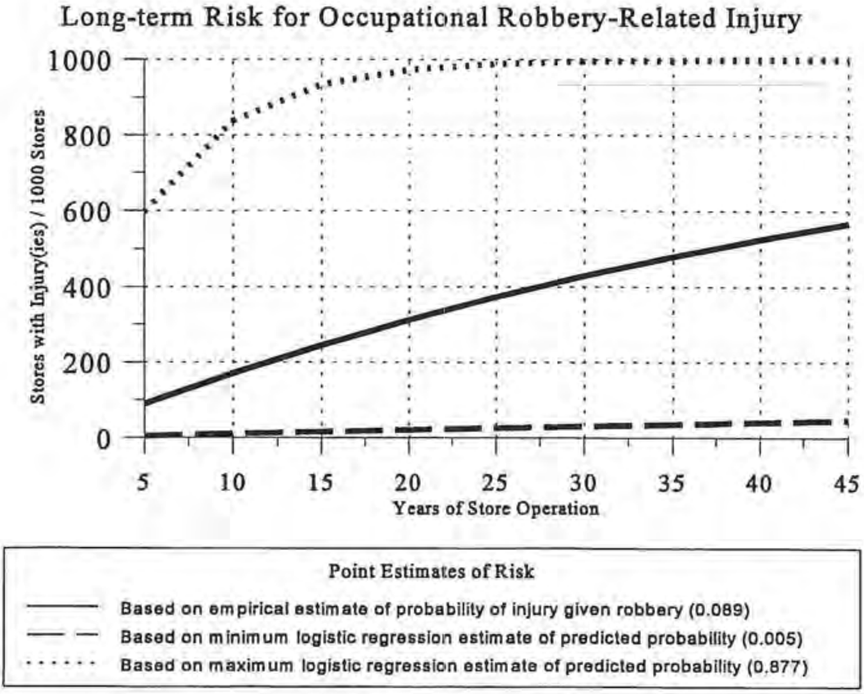

Figure 2. Lifetime risk in convenience stores for having an occupational robbery-related injury occurrence in which one or more employee(s) sustain at least one injury.

probability of injury conditional on robbery are representative of a subset of robbed stores in the population which had covariate values corresponding to the highest prediction of injury risk given robbery.

DISCUSSION

This study investigated the level of detail needed to accurately identify store populations at high-risk. Classification results indicate that high-risk convenience stores can usually be correctly identified using information concerning only the surrounding population and area and store and staff characteristics. However, in order to maximize classification accuracy, sensitivity, and specificity, and to minimize false positive and false negative rates of the model, circumstantial characteristics of the robbery need to be considered in the analysis. This limits the ability of investigators to identify populations at high risk for occupational robbery-related injury occurrence, since information on circumstances of robbery can only be collected after the robbery occurs.

This study also estimates a convenience store's lifetime risk over a range of years that a store could be in operation. The use of different logistic models to predict the probability of injury conditional on robbery leads to a wide variety of estimates for the probability of injury conditional on robbery. The results imply that, depending on individual characteristics of a store and the circumstances of robbery, the lifetime risk may vary tremendously. Empirical results indicate that convenience stores are, on average, at significant risk to experience an occupational robbery-related injury occurrence over any substantial amount of time in operation. After only 10 years of operation, for instance, convenience stores have a 17% probability for having an occupational robbery-related injury occurrence. The probability increases to 57% after 45 years. These results imply that for a population of a thousand stores operating from 10 to 45 years, the approximate range of convenience stores that will experience an occupational robbery-related injury occurrence is between 170 and 567.

These results support the importance of interventions to reduce the occurrence of occupational robbery-related injury in convenience stores. Past research in this field has largely focused on reducing robbery, with an additional objective of reducing the risk of robbery-related injury to convenience store workers (Amandus, 1993). Reducing the risk for robbery, assuming the risk for injury conditional on robbery stays constant, will reduce the overall risk of injury. However, decreasing the risk for injury conditional on robbery, assuming risk for robbery stays constant, would also lead to a decline in injury risk. The relative effectiveness of these approaches is unclear. The lifetime risk estimates assume a constant product for the values of robbery probability and injury conditional on robbery probability, over time. If the product of these values decreases over time, the calculations of the lifetime risk presented here would overestimate risk. The literature seems to indicate the probability of robbery is decreasing, but the direction of the probability of robbery-related injury, over time, is unclear since research has not thoroughly investigated the topic of robbery-related injury.

Several limitations and technical clarifications are important in interpreting study results. Very different results for the estimates of annual probability for occupational robbery-related injury occurrence would lead to very different estimates of lifetime risk. Separate calculations of the probability of robbery by important covariates, such as time of day, could lead to different risk estimates. This analysis also assumes equal exposure, which may not be completely accurate since not all stores were open 24 hours a day. Sample size restrictions, due to a limited number of occupational robbery-related injury occurrences, prohibited a more detailed analysis of these study data.

Estimates of classification accuracy may be positively biased for the purposes of future prediction since cross-validation methods were not implemented due to the limited number of outcomes. The generalizability of the study results may also be an issue since our study population was limited to convenience stores in selected metropolitan areas of Virginia. However, the annual distribution of robbery for the study population of convenience stores in the selected areas of Virginia over the first year is fairly consistent with 1990 national estimates, with only 17% and 20% of all stores, respectively, experiencing robbery (NACS, 1991). The annual distribution pattern of robbery for the selected areas in Virginia over the first year of the study also agrees with 1990 national estimates. Convenience stores experiencing only one robbery represent 13% of all convenience stores, both in the selected areas in Virginia over the first year and nationwide, while 11% of the stores in the selected areas in Virginia over the first year and 7% of the stores nationwide experience two or more robberies (NACS, 1991). Since researchers selected the eligible areas in Virginia such that both rural, suburban, and urban areas were included in the study, this may explain why the robbery distribution patterns seen in the study resembled the 1990 national estimates.

Future research in this area should attempt to collect a larger sample of robbery-related injury outcomes. Lifetime risk estimates could then be separately calculated for severe outcomes and different subgroups of convenience stores. Calculations of the probability for occupational robbery-related injury occurrence by time of day require a detailed analysis and knowledge of each store's hours of operation. This study lacked data on the hours of operation for many of the stores. Probability of robbery and probability of injury conditional on robbery are likely to vary by time of day (Amandus *et al.*, 1997).

Very few studies have analyzed the probability for occupational robbery-related injury occurrences in convenience stores. Amandus *et al.* (1996) and Schreiber (1991) both were able to calculate the probability of injury conditional on robbery, however a limitation of these studies is that the probability of robbery is unknown. This study makes an additional contribution to the convenience store robbery-related injury research by including two circumstantial factors: a clerk's resistance during robbery and the number of robbers. Amandus *et al.* (1997) and NACS (1987) previously suggested that circumstantial characteristics may heavily influence the risk of injury during a convenience store robbery. Classification results indicate that these circumstantial factors should be very carefully analyzed when considering opportunities for prevention programs.

This study examined two main topics: the lifetime risk for occupational robbery-related injury occurrence in convenience stores and the identification of store populations at high risk. Calculations of the risk for occupational robbery-related injury occurrence over a range of years that a store could be in operation indicate the large magnitude of this problem. These results underscore the importance of prevention methods in this setting. Identification of populations at high risk for injury given robbery should help guide researchers in selecting the appropriate study population. Future research, by expanding on the details of these analyses, will provide a valuable contribution to the risk assessment of occupational robbery-related injury occurrences in convenience stores.

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Evaluation of Occupational Injuries among Young Workers in West Virginia*

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ABSTRACT

We compared workplace injuries between young (16 to 19 years of age) and adult workers using West Virginia Workers' Compensation database. All workers injured between January 1 and December 31, 1995 were included in the analysis. The industry-specific injury incidence rates between young and adults workers were significantly different with lower rates of injury in young workers in all sectors except service sector. In the service sector the young workers had significantly higher injury rates than adults (rate ratios for young workers were 2.28, 1.92, and 2.94 when compared with age groups 20–24, 25–34, and >34, respectively). Estimates of the proportional injury ratio (PIR) indicated significantly greater risk of finger (PIR 1.62) and hand (PIR 1.66) injuries and burns (PIR 3.27) and lacerations (PIR 1.69) in the young workers. The proportion of injuries occurring in the summer months was higher in the young than in the adults (35.2% vs. 27.0%), particularly in the service sector (79.6% vs. 25.9%). Higher injury rates in young workers compared to adults in the service sector may be explained by the seasonal employment of young workers in West Virginia.

Key Words: adolescents, workers compensation, incidence rates, safety and health

INTRODUCTION

The Fair Labor Standards Act (FLSA) of 1938 protects underage workers in the United States from harmful exposures in the work place. However, its

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enforcement has been inconsistent across time and geographic jurisdictions (Pollack and Landrigan, 1990). A Center for Disease Control (CDC) Alert (1995) reported that each year approximately 70 youths under 18 years of age die from work-related injuries; 200,000 suffer work-related injuries, and 64,000 require treatment in a hospital emergency room (CDC 1982). Using data collected by NIOSH, Layne *et al.*, (1994) estimated that workers under 18 years of age had an injury rate of 5.8 per 100 full-time employee equivalents (FTE).

A number of studies present an estimate of occupational injury rates in young workers ranging from 1.9/100FTE to 8.6/100FTE nationally (Castillo, Landen, and Layne, 1994; Layne *et al.*, 1994; Brooks, Davis, Gallagher, 1993; Parker *et al.*, 1991) and many occurring during summer months (Runyan and Gerken, 1989). However, descriptive epidemiology of such injuries is still incompletely documented.

Although the burden of work-related injuries in West Virginia's workforce has not been well studied, the NIOSH state profile for West Virginia (www.cdc.gov/niosh/wv.html), shows that between 1980 to 1989, the average annual rate of work-place fatalities in West Virginia workers was more than double the national average (15.7/100,000 vs. 7.0/100,000 workers). It is speculated that the non-fatal injury rates are also higher than the national average. Very little is known about injury incidence rates either in the young or in the adult workers.

In this study we utilized the West Virginia Workers' Compensation (WVWC) claim database to determine the rates of injuries among young workers and compared the epidemiology of these injuries with adult workers. We have also compared summer and non-summer injuries among the young workers to evaluate the contribution of summer employment to injuries.

METHODS

Source of Data

Data were obtained from the West Virginia Bureau of Workers' Compensation (WVWC). West Virginia is one of six states in the nation that has state-managed workers' compensation insurance system. All employees are covered through this insurance system and the majority of the employers contribute to the fund to ensure workers' coverage. We evaluated injuries that occurred between January 1 and December 31 of 1995. During the 1995 calendar year 634,874 employees (other than federal) were reported to the West Virginia Bureau of Employment Programs. A majority was covered by the Workers' Compensation insurance system. Data on age were available on 59,035 (96.7%) claims. We excluded 128 cases, whose age was below 16, yielding a final sample of 58,907 cases. Information on gender, occupation, and industry of employment, nature of injury, cause of injury and the body parts injured were available on most claims using the WVWC codes. The industry of employment was based on categorization of National Council of Compensation Insurance (NCCI) coding used by West Virginia Workers' Compensation Division. The coding of nature of injury, cause of injury and body parts is based on in-house state-based classification. However, many of these classifications are similar to NCCI coding.

While comparing young and adult workers, we divided the adult workers into three age groups (20–24, 25–34, 35 and above) because the injury risk varies by age group. The young workers were then compared with each specific age group. The total number of employment for the age group 16–19 was obtained from the database of West Virginia Bureau of Employment Programs (WVBEP). During the calendar year 1995, 31,000 workers in this age group were employed in West Virginia. Information on industry specific employment by age group and gender was not available in the WVBEP database. There was a difference between West Virginia and USA in the percentages of labor force distribution in the mining (4.2% vs. 0.5%), agriculture forestry and fisheries (0.6% vs. 2.7%), and others (4.0% vs. 11.4%). However, there was very little difference in other major industries. We, therefore, estimated the gender, age and industry specific average employment in West Virginia for these comparable industrial sectors using the national estimates (Table 1) from current population survey (CPS) [Bureau of Labor Statistics, 1996].

Estimation of Injury Rates

We calculated industry specific incidence rates by dividing the numerator (number of injuries involving days away from work for different age and gender groups in specific industry category) by the total estimated employment in specific age-gender-industry groups in West Virginia. According to the WVWC, if a worker stays more than 3 days away from work due to accident, that worker is eligible for lost time compensation. Therefore, the numerator of the incidence rate contains all injuries that caused more than 3 days lost time. The rate ratios were calculated comparing specific age groups (20–24, 25–34, >34) with 16 to 19-year-olds. For each rate ratios 95% confidence interval was calculated using the method of Rothman (1986).

Proportional Injury Ratios (PIR)

These are based on proportions of injuries, or other injury related characteristics, in young and adult workers. The reason for using proportional injuries is the lack of denominator in injury risk variables. For example, we do not know what proportion of adult and young workers used hand tools. However, we have information on reported injuries that were associated with hand tools. Therefore, we used PIR analyses in this situation. The proportional injury ratios were calculated as follows: $PIR = (a/a+c) \div (b/b+d)$

Where: a = number of specific injuries in young workers
b = number of specific injuries in adult workers
c = number of all other injuries in young workers
d = number of all other injuries in adult workers

Table 1. **Age-specific percentage of workers by industry and gender in USA: Estimates using 1995 US Household Survey (CPS).**

	Men				Women			
Age groups	16–19	20–24	25–34	>=35	16–19	20–24	25–34	>=35
(N = in thousands)	N = 3281	N = 6557	N = 17131	N = 36246	N = 3111	N = 5713	N = 14346	N = 31806
Major industries	%	%	%	%	%	%	%	%
Construction	7.07	10.04	12.04	10.55	0.87	1.10	1.46	1.41
Manufacturing	9.33	18.82	21.66	23.44	4.08	9.49	12.36	12.35
Transportation and public utilities	1.52	4.58	5.95	7.22	0.71	1.96	3.12	2.85
Wholesale and retail	51.23	32.36	21.32	16.22	57.76	33.17	20.32	16.70
Service	21.91	23.93	24.97	26.18	31.12	42.69	47.32	51.12

Note: Total percentages do not add up to 100 because agriculture, mining, finance insurance real estate and public administration percentages are not shown.

Bureau of Labor Statistics: *Employment and Earnings* January 1996; Vol. 43 No.1, pp. 179.

Similar to proportionate mortality ratios commonly used in mortality statistics, the PIR convey an estimate of relative risk under certain assumptions. The 95% Confidence Intervals for PIRs were estimated by the method described by Rothman (1986). We have also computed the PIRs by comparing the proportions of summer injuries to that of non-summer injuries.

RESULTS

During the calendar year 1995, 2837 workers aged 16 to 19 years and 56,070 workers aged 20 years or more reported work-related injuries in West Virginia. The majority of injury claims for young workers came from service sector (47.8%) that included state and local government but excluded federal employment. The incidence rates of injuries involving days away from work showed higher rates of injuries among young workers in the service sector compared to other age groups (Table 2). We also observed gender differences

Table 2. Age-gender-industry specific incidence rate of work-related injuries involving days away from work in West Virginia, 1995.

	Men			
Age groups	16–19	20–24	25–34	>=35
Major industries	N (Rate/100)	N (Rate/100)	N (Rate/100)	N (Rate/100)
Construction	1118 (2.0)	3758 (3.6)	11780 (3.4)	21834 (2.6)
Manufacturing	1475 (2.2)	7047 (2.0)	21191 (2.0)	48517 (2.2)
Transportation and public utilities	241 (0.8)	1713 (3.7)	5824 (3.7)	14940 (3.2)
Wholesale and Retail	8100 (0.9)	12118 (1.6)	20854 (2.0)	33582 (1.8)
Service	3465 (4.6)	8960 (4.7)	24423 (2.9)	54194 (1.7)
	Women			
Construction	132 (0.8)	318 (2.8)	1054 (0.9)	2265 (1.3)
Manufacturing	620 (0.5)	2735 (0.5)	8943 (0.7)	19816 (0.9)
Transportation and public utilities	107 (0.9)	565 (0.2)	2260 (0.8)	4574 (1.0)
Wholesale and retail	8774 (0.4)	9562 (1.0)	14703 (1.2)	26796 (1.6)
Service	4726 (3.9)	12307 (2.2)	34172 (1.7)	81996 (1.2)

Note: N = Number of age-gender-industry specific employment for West Virginia was estimated by using the percentages from the U.S. labor force distribution shown in Table 1. The numerator for the rate came from number of injured workers involving days away from work.

in the injury incidence rates for both young and adult workers with male workers showing more than two-fold increased risk of injury compared to female workers. The comparison of age-industry specific rates between various age groups showed risk ratios of 1.92 to 2.94 while comparing the young to adult workers in the service sector (Table 3). The young workers showed lower injury risk ratios in other major industrial sectors.

Among the young workers, injuries were reported by the laborers (29.7%), food service workers (8.5 %), cooks (7.2%), and nurse aides (4.5%). The most frequently reported types of injuries among all age groups were sprains and lacerations. Table 4 shows PIR's by selected injured body parts, causes of injuries and nature of injuries. Young workers showed a 1.7 times greater risk of hand injuries and 1.6 times greater risk of finger injuries than adults did. In contrast, young workers experienced significantly decreased proportion of musculoskeletal stress injuries including back injuries. A comparison of causes of injuries between young workers and adult workers revealed increased risk of injury among young workers while working with hand tools (PIR 2.35; 95% CI 2.01–2.75). Young workers also had more than threefold increased risk of burn compared to adults but had significantly lower risk of musculoskeletal stress injuries (sprain). Fourteen percent of the injured young workers returned to work on the same day of sustaining the injury, and 83% returned within the first week of injury. Of the 2837 young workers, 35.7% (1015) were awarded compensation for lost time defined as days away from work longer than 3 days.

Evaluation of injuries revealed proportionally more injuries in the young workers during summer months than in non-summer months in the construction industry and service sector. However, the difference was statistically significant only for service sector ($p < 0.05$). The proportional injury ratios showed significant increase in bone fracture during summer (PIR 1.54; 95% CI 1.02–2.31). Comparison of the PIRs for injured body parts did not reveal any significant difference by summer and non-summer months either in the young or in the adult workers. The overall trend and PIRs did not alter significantly when we restricted our analysis to the lost time cases.

DISCUSSION

Our study results are consistent with but may show a bigger problem than the published reports on injury patterns seen in young workers elsewhere (Brooks and Davis, 1996; Castillo, Landen and Layne, 1994; Parker *et al.*, 1991). We have observed gender differences in injury rates in both the young and the adult workers. Among young workers, males showed more than twofold increased risk of injury compared to females in all industries except transportation and service industry. Similar increased risks in males were reported among Massachusetts teens by Brooks and Davis (1996) and by Layne *et al.* (1994) using the data on emergency room visits. Coleman and Sanderson (1983) also reported higher proportions of males (47%) than females (35%)

Table 3. Rate ratios comparing injury rates (involving days away from work) of young workers with other age groups.

	Rate of injury of reference age group 16–19 years	Rate ratio (95% CI) age group 20–24 years	Rate ratio (95% CI) age group 25–34 years	Rate ratio (95% CI) age group >34 years
Construction	1.92	0.54 (0.35–0.83)	0.60 (0.40–0.91)	0.78 (0.52–1.16)
Manufacturing	1.72	1.08 (0.75–1.54)	1.05 (0.75–1.47)	0.94 (0.67–1.30)
Transportation and public utilities	0.86	0.30 (0.10–0.96)	0.29 (0.10–0.92)	0.32 (0.10–1.0)
Wholesale and retail	0.64	0.48 (0.38–0.59)	0.38 (0.31–0.47)	0.38 (0.31–0.46)
Service	4.19	2.28 (1.13–1.46)	1.92 (1.71–2.16)	2.94 (2.63–3.29)

Table 4. Proportional injury ratios (PIR) by selected body parts among total injury cases, (1995): Comparison of young (age 16 to <20 years) and adult workers (age >20 years).

	Young worker (N = 2,837) Frequency of specific injury	Adult Worker (N = 56,070) Frequency of specific injury	Young vs. Adult PIR	(95% confidence interval)
Body parts				
Finger	553	6728	1.62	(1.50–1.76)
Hand	331	3946	1.66	(1.49–1.84)
Back	410	10829	0.74	(0.68–0.82)
Cause of Injury				
Hand tool	166	1397	2.35	(2.01–2.75)
Fall on Surface	918	16734	1.08	(1.03–1.15)
Nature of Injury				
Laceration	762	8877	1.69	(1.59–1.81)
Burn	165	997	3.27	(2.79–3.84)
Contusions	496	8566	1.14	(1.05–1.24)
Sprain	808	20645	0.77	(0.73–0.82)

seeking emergency room treatment for work related injuries. Although our data did not identify a marker of severity of injuries such as emergency room visits, it included injured workers who were away from work for more than 3 days indicating the severity of injuries. Therefore, the gender differences in injury rates observed in our study as well as in other studies among 16 to 19-year-olds may be due to differences in employment across various industrial sectors. Males are disproportionately employed in the industrial sectors that carry high injury incidence rates. Our data showed that male young workers were employed more frequently than female young workers in construction and manufacturing industries (Table 2). In contrast, more females were employed in traditionally low injury risk sectors such as wholesale and retail sector (57.6% females vs. 52.1% males), and service (31% vs. 22%). In the service sector the incidence of injuries involving days away from work did not vary by gender (RR = 1.18, 95% CI 0.96–1.45).

Young workers had an increased risk of hand and finger injuries and lacerations but decreased risk of back injuries compared to adults. These results are similar to that reported by Layne *et al.* (1994). Some of the hand and finger injuries can be attributed to the use of hand tools, as comparison of young to adult workers showed an increased risk of injury while using hand tools. Banco *et al.* (1997) identified a hand tool, known as a case cutter to be a frequent cause of lacerations among adolescent grocery store workers. Their study concluded that ergonomics and education can have a dramatic reduction in injuries, lost time and compensation costs from this cause. The increased hand injury risk among young workers may be due to many contributing factors such as lack of knowledge and training in proper use and handling of equipment, proper ergonomics and physical development of the adolescents.

The nature of injury evaluation revealed that lacerations were common in the service sectors. In West Virginia, the service sector employs young workers to clean school floors, walls and lockers as soon as school closes for summer break. Our finding of high injury rates as well as the higher proportion of summer injuries in this sector suggests that intervention programs targeting young workers who will be engaged in this type of employment are needed.

Comparison of West Virginia workers showed a greater than threefold increased risk of burns in the young workers. Parker *et al.* (1994) reported higher frequency of burns among high school students in Minnesota. A previous report suggests that burns occur most frequently in young workers employed in fast food restaurants and are commonly associated with the use of deep fryers (CDC-MMWR 1993). Kinney (1993) reported that the service sector, particularly the fast food industry, employs a large number of young workers. In this type of job no prior training or experience is required. Training in hazard recognition and prevention may reduce many of these injuries, especially burns. Protective equipment, especially engineering interventions may prove valuable as well.

Seasonality issue was important when we compared injuries reported from each industry and by occupation. The service sector reported more injuries during the summer months. Brooks *et al.* (1993) showed that the months with the highest number of injuries paralleled the highest employment of the young workers during summer months (June, July, August). According to the Bureau of Labor Statistics (BLS 1997), the number of workers aged 16 to 24 years grows sharply between April and July each year. Castillo *et al.*, (1994) reported that 44% of the occupational injury deaths occurred during the summer months (June to August). Targeting industrial sectors that employ more young workers during the summer months would be sensible for effective intervention.

There are a number of important limitations of our methodology. Our data covered only workers participating in the Workers' Compensation system. Therefore, the injury reporting may not be complete for all workers of the state. This means that we may have underestimated the numerator, particularly for less severe injuries. Despite this conservative estimate we have documented higher injury rates in young workers in the service sector than have been documented elsewhere.

The proportional injury ratio approach is valuable only for internal comparisons and assumes that reporting is equal among various age groups, (a weakness of all proportional rates). We excluded the very young workers under 16 years of age in our analysis of PIRs and incidence rates of injuries, because of small number. In addition, reliable denominator information was not available either in the national or in the West Virginia databases for workers less than 16 years of age. Therefore, they will require separate evaluation.

We identified that young workers in the service sector had the highest risk of injury particularly, in the summer months. There are many risks and benefits of adolescent labor (Fitzgerald and Laidlaw, 1995). However programs such as the state sponsored Schools-to-Work Programs which targets high school students can be encouraged to incorporate health and safety training in an effort to reduce some of these risks. We therefore recommend that occupational safety and health components be included in the school-based curriculum in order to properly prepare the young workers for safe and healthful working environments.

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Occupational Noise Sources and Exposures in Construction Industries

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ABSTRACT

This is an assessment of occupational noise exposures in the construction industry based on (1) noise measurements observed during Occupational Safety and Health Administration (OSHA) inspections over the period from 1986 through early 1997 and (2) the observed incidence of noise exposures over 85 dB(A) in a national random sample of construction firms done as part of the NIOSH National Occupational Exposure Survey (NOES) in 1981–83. The OSHA inspection data are analyzed by both industry categories and a classification system of equipment and occupational types based on free-form descriptions of "job title" by OSHA inspectors.

Because construction workers' jobs and work tasks change frequently, the noise observations within each industry were treated as a distribution indicating the fraction of time that workers would be likely to spend at various noise levels projected to a common year (1995). The time at each noise level in OSHA-measured dB(A) was summarized in terms of "90 dB(A) equivalents" using the "equal energy rule" which weights a day of exposure time at 100 dB(A), for example, as the equivalent of 10 days of exposure at 90 dB(A). Overall the 1995 projected exposures are slightly less than one "90 dB(A) equivalent" of continuous noise exposure per worker in the industry. This estimate is generally compatible with three other extensive sets of noise measurements for construction workers in the U.S. and Canada.

In further work the exposure estimates developed here will be used to project the hearing losses likely to result from work in construction industries. Those results will be compared with extensive available data on the hearing loss experience of construction workers in British Columbia. The results will

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form the basis for evaluation of the benefits of a variety of possible preventive measures.

Key Words: distributional analysis, dB(A), abrasive blasting, drills, jackhammers; chippers, concrete, painting, laborers

INTRODUCTION

Recent analyses of workers' compensation data from the State of Washington (Daniell *et al.*, 1998) and of older audiometric data from a national sample (Waitzman and Smith, 1998) indicate that workers in some sectors of the construction industry suffer hearing loss at a greater rate than workers in most other trades. Further study of the potential benefits of preventive measures therefore seems warranted.

This is an assessment of occupational noise exposures in the construction industry based on (1) noise measurements observed during OSHA inspections over the period from 1986 through early 1997 (Dubois, 1997, personal communication) and (2) the observed incidence of noise exposures over 85 dB(A) in a national random sample of construction firms done as part of the NIOSH National Occupational Exposure Survey (NOES) in 1981–83 (NIOSH, 1998b printout). These two data sources have complementary strengths and weaknesses.

- The OSHA inspection data provide considerable detail on noise sources, occupational and industry groups affected, and apparent trends in noise exposures over time to the present. On the other hand, OSHA compliance inspections are not designed as a random sample of the workplaces/industries monitored, and cannot therefore be used to directly assess the fraction of workers that are exposed at any one time in specific industry groups.

- The NOES was a stratified random sample of 4490 establishments from all U.S. industries. In the case of noise, the surveyors were equipped with sound level meters and recorded the number of workers at each site that was exposed over 85 dB(A), and the total number of production workers. They also recorded the fraction of noise exposed workers who were using personal protective equipment.

Together with allowance for the differences in time periods, these two sources provide some data on how many construction workers are exposed to how much noise.

Noise exposure in the construction industry has not been a major focus for OSHA. Noise measurements have been made only on a very small fraction of inspections in the industry—less than 1% based on the 22,700 construction inspections in 1994. Although the basic requirement for protection against 90 dB(A) 8-hour time weighted average exposures to noise does apply in construction, construction firms are currently exempt from the specific hearing conservation program standards that are mandated for employers in general manufacturing industries (OSHA, 1981, 1983). An OSHA priority planning document concludes a discussion of the issue of noise exposure in construction with the statement that "Rulemaking action to extend noise and hearing conservation protection to workers in the construction industry and other uncovered industries meets the criteria for designation as an OSHA priority" (OSHA, 1995). With the current publication of a revised NIOSH criteria document suggesting enhanced control of occupational noise exposure in general (NIOSH, 1998a, in press), and recent focused research by construction trades worker groups and NIOSH (Schneider *et al.*, 1995; Tennenbaum and Schneider, 1997; Waitzman and Smith, 1998; Prince *et al.*, 1997; Stephenson, undated), occupational noise exposures in construction will receive greater emphasis in the next few years.

This work addresses the potential benefits of different kinds of initiatives for control of noise exposures in construction. Possible initiatives are a construction specific standard on noise, labeling of equipment noise performance under standardized test conditions, "Buy Quiet" programs, and active encouragement of other voluntary actions/programs by employers, workers, and equipment suppliers. The analysis is guided by some distinctive features of the construction industry that pose challenges and opportunities for prevention efforts that are different from those in manufacturing industries. Unlike manufacturing jobs, construction jobs tend to be relatively short-term, and are done at dispersed locations with relatively few workers per site, with specific work tasks that vary from day to day as the work on a specific site proceeds. Many construction workers are likely to be exposed to highly varying conditions over the course of their careers, and thus not adequately monitored by stable, long-term employer-based industrial hygiene or medical surveillance programs.

Therefore, both the analysis and the eventual control of noise exposures in construction may benefit from a focus on specific types of equipment/operations in the form of vehicles or tools or processes (*e.g.*, abrasive blasting)—that may be responsible for much of the exposure. An equipment-based approach may facilitate the assessment of worker exposures, hearing loss risks, and potential benefits from new initiatives by OSHA. An equipment focus may also allow assessment of possibilities for progress toward noise control via two non-OSHA-standard setting pathways: (1) voluntary agreements with the manufacturers of specific types of equipment to achieve specific noise control performance improvements for new equipment marketed in the future, and (2) local governmental equipment performance standards, taking into account the nuisance and disruption that can be caused for communities by noise from construction equipment that may be greater than necessary with the best available construction techniques and noise control technology. Manufacturers of new equipment may find some voluntary agreements on performance standards attractive because they could help publicize the capabilities and desirability of their newer products, thus facilitating sales.

The analysis below therefore exhibits the available data by both traditional industry groupings, and by a set of equipment/occupation categories created from a free-form description of "job title" recorded by the OSHA inspectors (Table 1). The traditional industry groupings allow the inspection data to be associated with the numbers of workers in various sectors and NIOSH 1981–83 data on the fractions of workers exposed at ≥ 85 dB(A) in a representative sample of workplaces in different industries. This provides the basis for estimates of the population aggregate noise exposures in different industries. The information based on job titles allows some inferences to be drawn of the relative amounts of exposure associated with different occupations and types of equipment, both in general for the construction industry, and within specific industry groups that are identified as particularly problematic in the industry analysis. An earlier report to OSHA has more detail on some of these analyses (Hattis, 1997).

DISTRIBUTION OF MEASURED NOISE EXPOSURES, AND TIME TRENDS

OSHA inspection and noise measurement data for the construction industry (Standard Industrial Codes 15-17) were compiled from 1979 to the present. 1,989 records were retrieved where individual noise readings were made (often several readings per inspection), although no actual noise levels are included for inspections conducted before 1984. Figure 1 shows the distribution of 1034 reported noise levels in dB(A) after the elimination of 910 blanks (417 from records before 1984) and likely data errors. The latter included 10 values below 60; and 33 values between 60 and 74, and one reported value of "8806".

The two parts of Figure 1 show the data (a) in histogram form and (b) as a probability plot (Hattis and Burmaster, 1994). For the latter plot, the points represent the cumulative percentages of the data that were below various dB(A) levels, spaced at 5 dB(A) intervals. For plotting, the cumulative percentages are transformed into "Z-Scores" which represent the number of standard deviations above the mean of a normal distribution that would be needed to have the area under the normal curve below that point correspond to the cumulative percentile of the noise distribution data. In the regression line from this kind of a plot, the intercept is an estimate of the mean and the slope is an estimate of the standard deviation of the data.

Figure 2 presents a similar probability plot of an independent set of 837 noise measurements done between 1980 and 1984 in the British Columbia construction industry by the Workers' Compensation Board of British Columbia at the inception of major activities in hearing conservation (Harrison, personal communication, 1998) when that group made a major effort to characterize representative exposures. It can be seen that these data are also quite compatible with a normal distribution, although the indicated standard deviation (slope of the regression line) is somewhat smaller than for the OSHA data.

Table 1. Categories of noise sources and occupations from "job title" information.

1. **Categories based on noise source**[a]
   - **1.1. Noise of a part of the machine acting on a target**
     - 1.1.1. Operators of cutting machines, n.e.c. (not elsewhere classified)
     - 1.1.2. Chippers (except jackhammers)
     - 1.1.3. Jackhammers and related equipment
     - 1.1.4. Drills
     - 1.1.5. Operators of machines for modifying surfaces (except blasters)
     - 1.1.6. Operators of crushing and grinding machines
     - 1.1.7. Pile drivers
     - 1.1.8. Press operators
   - **1.2. Noise from collisions/energy dissipated outside the machine**
     - 1.2.1. Abrasive/sand/shot blasters
     - 1.2.2. Other machines using compressed air
     - 1.2.3. Machines spraying compressed liquids
   - **1.3. Engine noise primarily**
     - 1.3.1. Operators of material handling/transport/miscellaneous machines
     - 1.3.2. Paving/grading/road construction
     - 1.3.3. Back hoe/bulldozer/bob cat/front end loader operators
     - 1.3.4. Crane workers
     - 1.3.5. Drivers, truck and not otherwise specified
2. **Categories based on occupation/type of work**
   - 2.1. Electricians (includes "wiremen")
   - 2.2. Brick layers/masons/hod carriers, n.e.c.
   - 2.3. Boiler makers
   - 2.4. Welders, n.e.c.
   - 2.5. Assemblers
   - 2.6. Carpenters, millwrights, drywall workers
   - 2.7. Grounds keepers
   - 2.8. Insulation workers
   - 2.9. Iron workers
   - 2.10. Mechanics

Table 1. Categories of noise sources and occupations from "job title" information. (continued)

2. Categories based on occupation/type of work

2.11. Painters

2.12. Plumbers and pipe fitters

2.13. Sheet metal workers

2.14. Supervisors

2.15. Laborers, helpers, equipment cleaners

2.16. Other/miscellaneous occupations

[a] This system defines three broad types of equipment according to the kind of process that is thought most likely to be responsible for generating most of the noise. Equipment that makes noise by the action of a part of the machine on material outside the machine (*e.g.*, a saw or other cutting device category 1.1) was deistinguished from equipment where much of the energy producing the noise originates from events entirely outside of the machine (*e.g.*, abrasive hitting an external surface, as in abrasive blasting, category 1.2), and equipment where the predominant noise source appears likely to be an engine (category 1.3). These categories may capture broad groups of problem types with different opportunities for abatement.

The absolute values of these Canadian dB(A) measurements are not comparable to the OSHA measurements because they are based on the "equal energy" 3 dB(A) rule for trading a doubling of exposure time for different noise intensities, rather than OSHA's 5 dB(A) doubling rule. For example, in OSHA's measurements, 4 hours of exposure at 95 dB(A) are considered equivalent to 8 hours of exposure at 90 dB(A) whereas the Canadian measurements would treat 4 hours of exposure at 93 dB(A) as equivalent to 8 hours of exposure to 90 dB(A). NIOSH (1998a) has recently recommended that the 3 dB trading rule be adopted for noise measurements and mandatory regulations in the U.S. because this "equal energy" rule is more closely related to the damaging effects of noise exposures at different levels of intensity. The difference between the two time-averaging systems may be particularly important for construction industry exposures because many construction workers are likely to change their job tasks and exposures more frequently than would be the case for most workers in manufacturing jobs. Seixas *et al.* (1998) have recently found a difference averaging 7.2 dB(A) in 174 sets of parallel measurements using the 3-dB(A) and 5-dB(A) trading rules in workers engaged in heavy nonresidential construction (SIC 154).

OSHA NOISE MEASUREMENTS BY TYPES OF INSPECTIONS AND TEMPORAL CHARACTERISTICS OF REPORTED EXPOSURES

Table 2 is a summary of the OSHA data by types of inspections. Conversations with the OSHA Office of Compliance indicate that two of these catego-

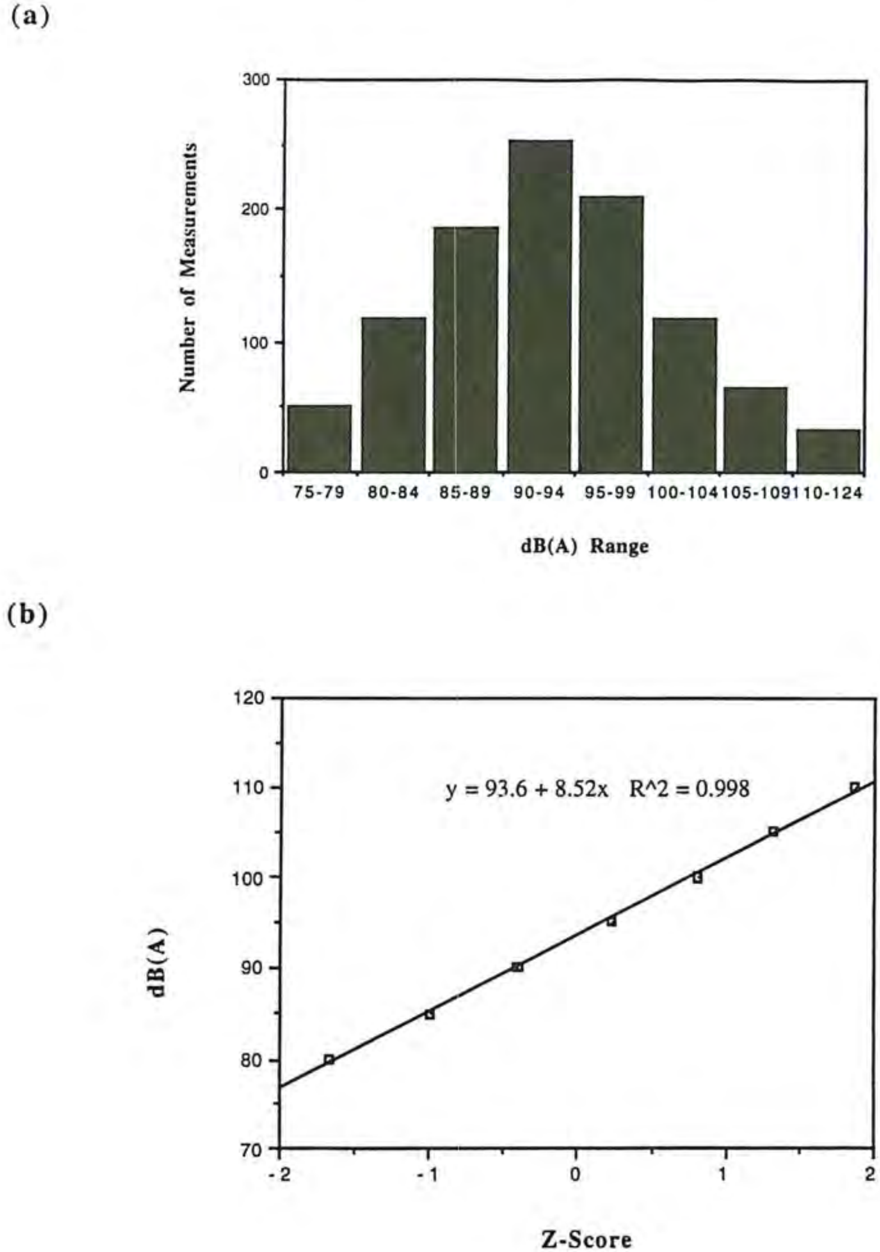

Figure 1. Distribution of OSHA construction industry noise exposure measurements reported in a valid range [75–124 dB(A)]. (a) Histogram. (b) Probability plot.

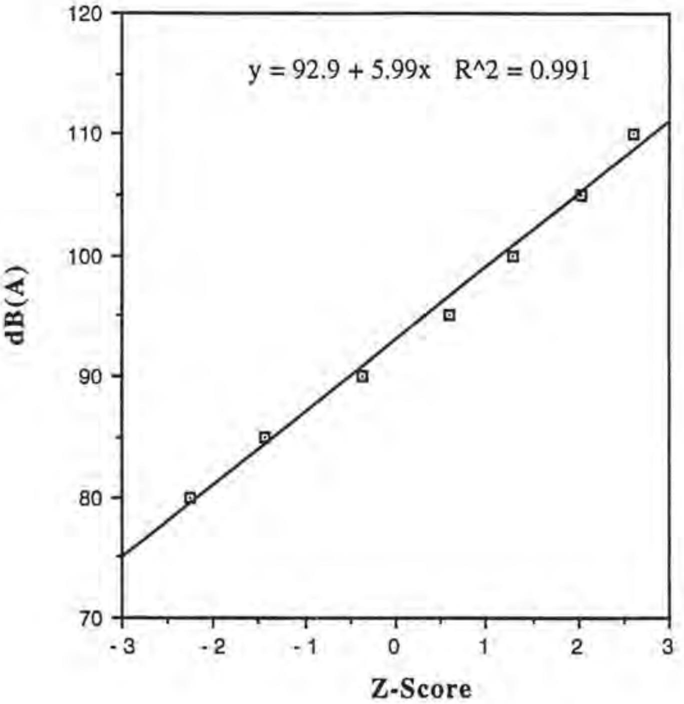

Figure 2. Probability plot of Leq (3 dB Trading Rule) noise measurements in construction by the British Columbia Workers Compensation Board (Harrrison, 1998).

ries ("programmed" and program-related) are likely to reflect firms selected for inspection without significant prior information that those firms had unusual noise exposures (Richard Fairfax, 1998, personal communication)—and the data in the table indicate lower average noise levels for these inspection types. Therefore, in later multiple regression analyses, these inspection types will make up the reference category for which ultimate projections of noise exposures will be made after statistical control for the higher average noise readings observed for inspections of other types. This allows use of the data for other types of inspections without biasing the ultimate projections of likely exposures.

Table 3 is a summary of the data by two exposure-time characteristics that are often recorded by the OSHA industrial hygienists—long-term days or hours per week or per month (Table 3a), and short-term hours/day (Table 3b). The reported OSHA noise measurements incorporate a correction for the time of exposure on the day of measurement, but will not usually reflect an allowance for long-term duration of exposure. Among those records where a specific statement is made on each type of exposure-time characteristic, the

Table 2. Summary of noise measurements and time trends by inspection type.

Inspection type	Mean dB(A) for samples ≥ 75 dB(A)	Std. error of mean	Number of samples ≥ 75 dB(A)	Coefficient of time trend (dB(A)/Year)	Std. error of time trend
Complaint (response to worker complaint)	92.3	0.6	228	–0.19	0.16
Referral (from another governmental agency or from a safety to a health inspector)	95.7	0.5	325	–0.08	0.12
Programmed (inspection initiated by OSHA)	90.6	0.5	257	–0.29	0.11
Program-Related (inspection of another employer present at the site of a programmed inspection)	91.4	1.2	46	–0.42	0.28
Unprogram-Related (inspection of another employer present at the site of a complaint, referral or other type of inspection)	93.6	0.7	133	–0.45	0.22
Other	89.1	1.3	45	–0.04	0.31
Programmed and program-related combined	90.7	0.4	303	–0.30	0.10

Table 3. Summary of noise measurements by exposure-time characteristics.

	Mean dBA for samples ≥ 75 dBA	Std. error of mean	Number of samples ≥ 75 dBA	Coefficient of time trend (dBA/year)	Std. error of time trend
(a) Separation by Long-Term Duration of Exposure					
Full time (≥ 4 days/ week or equivalent)	92.1	0.5	302	-0.28	0.14
Less than full time	93.5	0.8	126	–0.18	0.23
Days/year not stated	93.2	0.3	606	–0.18	0.08
(b) Separation by Fraction of the Day Exposed					
Full shift (>6 hrs/day)	93.1	0.3	591	–0.06	0.09
≤ 6 hrs/day total	92.5	0.6	149	–0.55	0.16
Hours/day not stated	93.0	0.5	294	–0.38	0.14

majority of the readings are reported to reflect full time rather than part time exposures. These exposure-time breakdowns generally do not reveal statistically significant differences in mean noise levels, although for reasons that are not yet clear, the measurements for workers exposed for a full shift do not show the same tendency for reduction over time that is apparent for other measurements. The previously cited discussion with the OSHA compliance office indicated that there has been no change in the official directions to field personnel for calculating and reporting the time-weighted-average levels that could have artificially created a bias toward lower noise levels for workers exposed for less than a full shift in more recent years.

MULTIPLE REGRESSION ANALYSES USING EQUIPMENT-OCCUPATION AND INDUSTRY CATEGORIES

Tables 4 and 5 show the results of "stepwise" multiple regression analyses intended to identify the equipment/occupation and industry groups associated with relatively high noise exposures, after control for inspection types and the apparent time trend in the data. The "stepwise" regression for the equipment/occupation types was begun by entering all the categories defined in Table 1 at the outset, and then eliminating those categories in turn which showed the least statistically significant differences from a reference category (initially, assemblers) with relatively low average noise exposure levels. This process was repeated until all remaining categories differed from the reference group at $P < 0.05$. For the industry groups, the initial reference category was SIC 175 — carpentry and floor laying.

For Tables 4 and 5, the end result is an equation with noise levels in dB(A) as the dependent variable, and regression coefficients for the independent variables defined in the first column of numbers. For example, the equation for Table 4 is:

> noise level in dB(A) = intercept – 0.18*(sample year, expressed in 2 digits—*e.g.*, 95 for 1995) + 9.3 (for chipping machines) or + 3.9 (for jack hammers) or + 9.3 (for drills) or + 8.1 (pile drivers) or + 10.9 (for press operators) or + 9.0 (for abrasive blasting) or + 3.0 (for laborers) or + 1.6 (for complaint inspections) or + 3.4 (for referral inspections) or + 3.0 (for unprogram-related inspections) or –.7 (for other inspections, except for the reference inspection types—programmed and program-related).

It can be seen in both tables that the coefficient for "sample year" is highly significant statistically (P much less than 0.01, seen in the next to last column). The value of this coefficient indicates a decline in noise exposures at a rate of about 2 dB(A) per decade. Based on this, the final column of each table gives predicted average noise levels in dB(A) for each equipment/occupation and industry category for program and program-related inspections in 1995.

Table 4. Multiple regression, including time trend and equipment/occupation groups significantly greater than the residual category at $P < 0.05$, with control for inspection types.

Summary of Fit

Rsquare	0.22
Root Mean Square Error	7.45
Mean of Response	92.95
Observations	1034

Estimates

Term	Regression coefficient	Std error	P-Value	Model-predicted average dB(A) in 1995
Intercept	105.5	5.6	<0.0001	
Sample year	–0.18	0.06	0.003	
Chipping nec	9.3	2.0	<0.0001	98.2
Jack hammers	3.9	2.0	0.045	92.7
Drills	9.3	1.4	<0.0001	98.6
Pile driver	8.1	2.8	0.004	97.4
Press	10.9	2.6	<0.0001	98.9
Abrasive blasting	9.0	0.8	<0.0001	97.8
Laborers helpers, equipment cleaners	3.0	0.6	<0.0001	92.0

Other equipment or occupation categories				88.6
Complaint inspections	1.6	0.7	0.02	
Referral inspections	3.4	0.6	<0.0001	
Unprogram-related inspections	3.0	0.8	0.0001	
Other inspections	–0.7	1.2	0.55	

Table 5. Multiple regression including time trend and industry groups significantly greater than the residual category at $P < 0.05$, with control for inspection types.

Summary of Fit

Rsquare	0.16
Root Mean Square Error	7.77
Mean of Response	92.95
Observations	1034

Estimates

Term	Regression coefficient	Std error	P-Value	Model-predicted average dB(A) in 1995
Intercept	105.2	6.1	<0.0001	
Sample year	–0.22	0.07	0.0012	
154 Nonresidential build.	7.0	1.3	<0.0001	91.6
161 Highways and streets	3.7	1.1	0.001	88.3
162 Other heavy	5.9	1.1	<0.0001	90.5
171 Plumbing heating air cond	4.4	1.5	0.0033	89.0
172 Painting, paperhang.	10.1	1.2	<0.0001	94.7
174 Total	5.6	1.4	0.0001	90.3
176 Roofing siding sheet metal	5.9	2.0	0.0033	90.5
177 Concrete	9.7	1.5	<0.0001	94.3
179 178 Total	4.6	1.1	<0.0001	89.2

Other construction industries				84.7
Complaint inspections	1.6	0.7	0.03	
Referral inspections	3.8	0.6	<0.0001	
Unprogram-related inspections	2.5	0.8	0.003	
Other inspections	-0.6	1.3	0.66	

The two industries that stand out in the industry analyses are "Painting and Paperhanging" (SIC 172) and "Concrete" (SIC 177). In earlier work it was found that the major source of high noise measurements in the "Painting and Paperhanging" industry was abrasive blasting (Hattis, 1997). Over 10% of all the measurements analyzed across all industries identified abrasive blasting as the source, and these averaged over 100 dB(A). Other source categories with relatively high noise levels and potential interest for focused control efforts are drills (especially in SIC 154), and chippers, jack hammers, and "other cutting machines" in SIC 162. Among occupational groups, laborers tend to have higher noise exposures than others represented in the data.

INDUSTRY NOISE EXPOSURE ESTIMATES USING NIOSH AND OSHA DATA

Table 6 shows the 1981-83 NIOSH/National Occupational Exposure Assessment estimates of the percentage of workers in 3-digit SIC industry categories exposed to noise over 85 dB(A), and the fraction of those exposed that were observed using personal hearing protectors such as ear plugs or ear muffs. These data indicate that at the time of the survey (a) a minority of construction industry workers were exposed to noise levels over 85 dB(A), and (b) of those exposed, relatively few were using hearing protectors. In a recent survey of 400 construction workers, Lusk *et al.* (1998) find that only about a third report consistent hearing protector use when they are exposed to high noise levels, although this is more than the approximately 15% directly observed by the National Occupational Exposure Survey (NOES) in 1981–3.

There are two challenges in combining these data with the results of the regression analysis of OSHA inspection data in Table 5 to give overall estimates of exposure:

- Because of the time trend toward reduction in noise levels observed in the OSHA data, it is necessary to correct for the difference in expected noise exposure levels between 1981–3 and the more recent year (1995) that will be the basis for projection of current conditions.

- NOES surveyors counted only those workers exposed to ≥ 85 dB(A), however, the OSHA data extend down to 75 dB(A). Therefore, a fraction of the population "exposed" to the noise level distribution indicated by the OSHA data would not have been counted as "exposed" in the NOES survey. It is necessary to correct for this difference by increasing the fraction "exposed" as defined by NOES for those who would have been counted as "exposed" if the cutoff had been 75 dB(A).

A further challenge is to appropriately represent the effect of the changes in exposure that workers experience as they move from job to job within each industry. The key to meeting these challenges is to treat the regression modeling results from Table 5 in distributional form. For example, it can be seen in Table 5 that the noise-exposed workers monitored by OSHA in the plumb-

Table 6. Aggregate 1995 employment data and NIOSH observations of noise exposures and hearing protector use in 1981–83.

SIC	Industry Description	1995— Thousands of employees	NIOSH % exposed ≥ 85 dB(A) in 1981–83	Reported % of those exposed using hearing protectors
152	Residential builders	609	12.4	1
153	Operative builders	27		
154	Nonresidential buildings	567	11.7	15
161	Highway and street construction	223	27.1	11
162	Other heavy construction	526	17.2	44
171	Plumbing, heating, air conditioning	712	7.4	16
172	Painting and paperhanging	179	19.6	0
173	Electrical work	593	12.5	0
174	Masonry, stonework and plastering	409	8.2	11
175	Carpentry and floor laying	219	32.3	0
176	Roofing, siding, and sheet metal	208	10.7	3
177	Concrete work	248	39.7	19
178	Water well drilling	21		
179	Miscellaneous special trade contractors	548	13.6	35
	Total	5,089		15

ing, heating and air conditioning industry are expected to have an average exposure of 89 dB(A) in 1995. However over time, as the workers move from task to task and job to job it is more realistic to say that they have a distribution of exposures given by this mean and a standard deviation corresponding to the "root mean square error" of about 7.8 dB(A) shown in the upper portion of the table. Assuming a normal distribution, this indicates, for example, that they are likely to spend about 22% of their time over 95 dB(A), 8% of their time over 100 dB(A), and 2% of their time over 105 dB(A). Under the "equal energy rule" for summarizing noise dosage (NIOSH, 1996; Suter, 1992), a worker spending 8% of work time at 100 dB(A) is expected to suffer an approximately equal amount of damage as a worker who spends 80% of work time at 90 dB(A)—that is, approximately 0.8 "90 dB(A) equivalents". More formally this analysis calculates a Population Aggregate Noise Exposures (PANE) in terms of 90 dB(A) equivalents as:

$$\text{PANE} = \sum_i \text{fraction of work time}_i * 10^{(W_i - 90)/10}$$

Where the W_i are the noise levels in dB(A) prevailing for various fractions of the work time within each industry group. Within each industry the "exposed workers" are assumed to experience dB(A) levels that are normally distributed with the standard deviation given by the mean square error shown in Table 5. (Figure 3 shows a plot of the "residuals" from the industry regression — the observed dB(A) levels less the model-predicted levels. It can be seen that these are approximately normally distributed, although there is some excess of

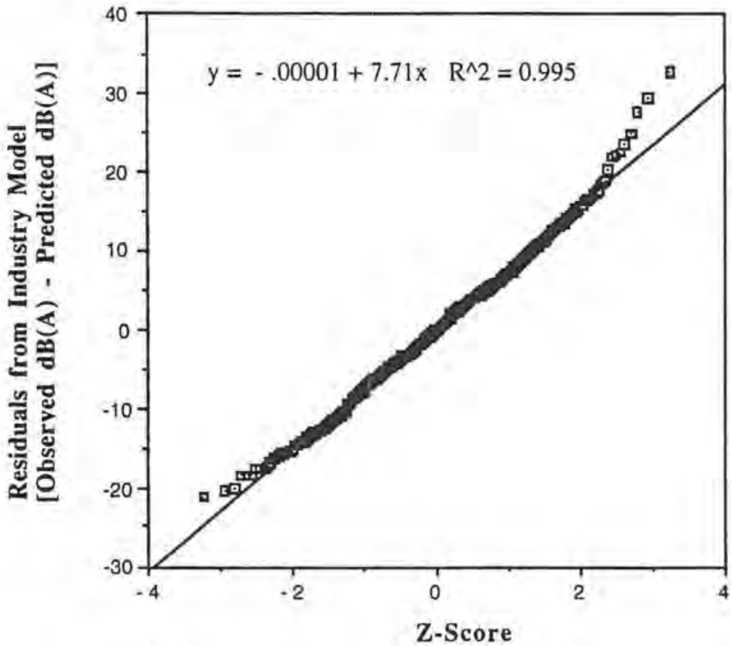

Figure 3. Probability plot of the distribution of residuals from the industry regression (Table 5).

particularly large residuals — over 20 dB(A)—that is not fully captured by the normal distribution indicated by the straight line in the figure. Nine of the 1034 data points are in this region. The effect of assuming a normal distribution here is essentially to discount the additional contribution of this modest number of very large positive departures from model-expected noise exposures).

A second key assumption is needed to link the OSHA data with the NIOSH/NOES data. This is that within an industry, the fraction of work time that the workers are "exposed" to the distribution derived from the OSHA inspection data (for programmed and program-related inspections) corresponds to an adjusted fraction of workers classified by NIOSH as exposed ≥ 85 dB(A). The adjustment is made by calculating the fraction of exposed workers in each industry from the OSHA data that would have been expected to be classified as "exposed" ≥ 85 dB(A) by the NIOSH surveyors in 1982 (third column of Table 7), and using this to estimate the higher fraction of workers who would have been classified as "exposed" if the surveyors had used a 75 dB(A) cutoff (fourth column of Table 7).

The last four columns of Table 7 give aggregate exposure estimates based on the exposure time distributions and the equal energy rule as described above. For example, for the plumbing industry, it can be seen in the sixth column that the predicted average exposures of 89 dB(A) are projected to deliver four "90 dB(A) equivalents" per exposed worker. This is because with a standard deviation for the exposure distribution of over 7 dB(A), an appreciable portion of the exposure time is expected to be spent well above 90 dB(A), heavily influencing the population average noise exposure. In column 7 it can be seen that this translates into about 0.36 "90 dB(A) equivalents" per total worker in the industry, considering that the workers would be expected to be "exposed" to the OSHA-derived noise distribution for only about 9% of the time, based on the observations of the NIOSH/NOES surveyors, adjusted in the way described earlier.

Table 7 does not reflect any downward adjustment for effective reduction in noise exposures from the use of hearing protectors. It also does not reflect any upward adjustment for the use of a 5 dB(A) doubling rule in making the original noise measurements. Even with these caveats, however, the projections in Table 7 indicate substantial potential for "material impairment" of construction workers' hearing. The aggregate of 4.7 million "90 dB(A) equivalents" of potential exposure for 1995 calculated on the bottom line of the table is about 0.92 for each worker in the industry.

COMPARISONS WITH OTHER DATA SOURCES

There is one recently collected set of data that can provide the basis for a direct comparison with one of the projections in Table 7. Seixas *et al.* (1998) have studied noise exposures for workers on heavy construction projects (SIC 154) in Washington State. In all Seixas *et al.* report 338 full workshift samples,

Table 7. Population aggregate noise exposures by industry for 1995 (before accounting for abatements from the use of hearing protectors).

SIC	Description	1982 Fract workers "exposed" to the OSHA-derived distribution expected over 85 dB(A)	Inferred total % noise exposed population (≥75) in 1981–83	Est. 1995 mean dB(A) exposure for those "exposed" ≥75	90 dBA equiv/ worker "exposed"	90 dBA equiv/total workers in SIC	90 dBA equiv. X no. workers (thousands)	% total const. industry 90 dBA equiv.
152, 153	Residential and operative builders	0.62	19.9	84.7	1.4	0.29	180	4
154	Nonresidential buildings	0.89	13.2	91.6	7.0	0.93	520	11
161	Highway, street construction	0.79	34.4	88.3	3.4	1.16	260	6
162	Other heavy construction	0.86	20.0	90.5	5.5	1.10	580	12
171	Plumbing, heating, air conditioning	0.81	9.2	89.0	4.0	0.36	260	5
172	Painting and paperhang.	0.95	20.7	94.7	13.7	2.84	510	11
173	Electrical work	0.62	20.1	84.7	1.4	0.29	170	4

174	Masonry, stonework plastering	0.85	9.6	90.3	5.2	0.50	200	4
175	Carpentry and floor laying	0.62	51.7	84.7	1.4	0.75	160	4
176	Roofing, siding, and sheet metal	0.86	12.5	90.5	5.5	0.69	140	3
177	Concrete work	0.94	42.2	94.3	12.7	5.35	1320	28
178, 179	Miscellaneous special trade contractors	0.82	16.6	89.2	4.1	0.68	390	8
	Total					0.92	4710	100

taken in such a way as to fairly represent the exposures on four worksites for four different construction trades. Table 8 shows the results of using the means and standard deviations of reported noise levels from these observations to calculate population aggregate noise exposures via the equation given earlier. In this case, because Seixas *et al.* (1998) directly recorded the exposures of typical workers, regardless of whether they were judged to be exposed above any given noise level, there is no need for an exposure time adjustment as was done for column 7 of Table 7. It can be seen in Table 8 that the overall average of about 0.63 "90 dB(A) equivalents" per worker observed by Seixas *et al.* (1998) is well within a twofold range of the value of 0.93 dB(A) projected nationally for this SIC code for 1995 in Table 7. This provides some modest support for the exposure estimates in Table 7.

Some other comparisons are possible based on two sets of Canadian data, with an adjustment for the difference between the 3 dB(A) doubling time/intensity rule used in Canada and the 5 dB(A) rule used by OSHA. The distribution for the more extensive of these Canadian data sets has already been displayed in Figure 2. The 874 observations have a mean of 91.9 dB(A) and a standard deviation of 5.7 dB(A). After subtracting the 7.2 dB(A) difference observed by Seixas *et al.* (1998) in their 174 parallel measurements using the 3 dB(A) and 5 dB(A) doubling rules, the mean of comparable OSHA measurements would be expected to be about 84.7 dB(A). Finally, applying the "equal energy" formula provided earlier, this translates into an average of 0.69 dB(A) equivalents per worker in the industry.

Finally Sinclair and Haflidson (1995) give distributional data for noise exposures for 104 workers in several construction trades in Ontario, Canada. Figure 4 summarizes these in the same format used for Figures 1 and 2. Making the same conversion between the 3 dB (A) and 5 dB(A) doubling rules as in the previous paragraph, these data translate into an average of about 1.4

Table 8. 90 dB(A) equivalents for workers in SIC 154 in the State of Washington studied by Seixas *et al.* (1998).

Trade	N	Mean dB(A) [OSHA 5 dB(A) doubling rule]	Standard deviation	90 dB(A) equiv./worker
Carpenter	122	82.2	7.7	0.79
Laborer	113	83.3	7.1	0.81
Ironworker	55	82.3	5.9	0.41
Operating engineer	48	83.5	4.5	0.37
Total	338	82.8	6.8	0.64

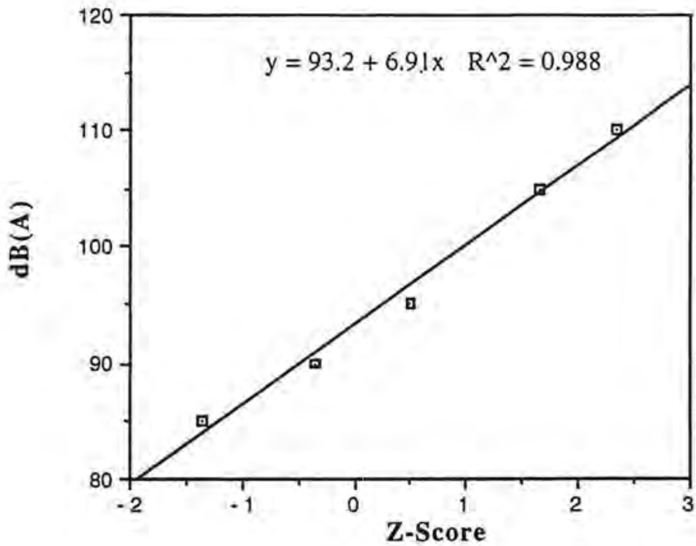

Figure 4. Probability plot of Leq (3 dB trading rule) construction industry noise exposure measurements reported for Ontario, Canada, by Sinclair and Haflidson (1995).

"90 dB(A) equivalents" per average worker in terms of the OSHA 5 dB(A) doubling rule. Overall, therefore, the two Canadian data sets yield estimates of average construction worker exposures in "90 dB(A) equivalents" that bracket the average of 0.92 dB(A) equivalents per U.S. construction worker projected in Table 7. Despite this encouraging result, it would still be desirable to make further comparisons of these projections with additional current data collected for representative samples of workers on U.S. construction sites.

CONCLUSIONS AND PLANS FOR FURTHER WORK

A further set of comparisons is possible utilizing data on observed hearing losses among different construction industries vs those that might be expected based on Table 7, together with available information on the usage and efficacy of hearing protectors. The most promising data of this type is an extensive compilation of information from mandated routine audiograms in British Columbia, which have recently been made available by the British Columbia Workers Compensation Board (Harrison, 1998). In all, these data cover 30,698 audiograms collected near the start of the program in 1988, and 43,009 audiograms from 1997. Additional, but much less extensive data of this sort appear to be available for roofers (Tennenbaum and Schneider, 1997), for sheet metal workers from an older study (Kenney and Ayer, 1975), and from the first National Health and Examination Survey measurements, which have recently been analyzed for construction workers by Waitzman and Smith (1998). With the verification of exposures and effects that is possible on the basis of such comparisons, and perhaps also with some supplementary programmed measurements of representative workplaces and workers by OSHA, national preventive measures could be designed, targeted, and evaluated with even greater confidence.

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Human and Ecological Risk Assessment (HERA)

Aims and Scope

Human and Ecological Risk Assessment is the first journal devoted to providing a framework for professionals researching and assessing developments in both human and ecological risk assessment. The journal was created to enhance the communication and cooperation of professionals working on human risk assessment with those in the ecological risk assessment domain. Given the rapid development in these respective disciplines and their unique potential interrelatedness, efforts to directly enhance technical information transfer will markedly benefit each field. The journal will be a quarterly, international, peer-reviewed publication focusing on scientific and technical information and critical analysis in the following areas:

- Exposure Assessment
- Environmental Fate Assessment
- Hazard Assessment
- Use of Uncertainty Factors
- Animal Extrapolation
- Quantitative Risk Assessment
- Epidemiology
- Laboratory/Field Extrapolation
- Multi-Media Assessment
- Risk Management
- Regulatory Issues
- Databases
- Pharmacokinetic Modeling
- Risk Communication

Manuscripts will be considered that address any of the wide range of issues associated with the entire risk assessment process. Example of the types of manuscripts encouraged for submittal include:

- Original data on relevant topics (*e.g.*, exposure and hazard assessment)
- Critical reviews of current methods for risk assessment
- Improved extrapolation methods (*e.g.*, interspecies, route-to-route, high to low dose)
- Biological mechanism-based risk assessment procedures
- Improved biomathematical modeling
- International approaches
- Case studies
- Commentaries
- Technical debates
- Editorials

Table of Contents

SPECIAL ISSUE:
Occupational Injury Risk Assessment
James T. Wassell, Guest Editor
A. John Bailer, Guest Editor

Perspective:
Occupational Injury Risk Assessment: Perspective and Introduction
by Linda Rosenstock and Nancy Stout 1255

Debate/Commentary:
Injury Risk Assessment for Occupational Safety Standards
by J.F. Martonik, E.A. Grossman and C.P. Gordon 1259

Comparing Injury and Illness Risk Assessments for Occupational Hazards
by A. John Bailer, Leslie T. Stayner, William Halperin, Laurence D. Reed and Tom Seymour 1265

Probability Models of Occupational Injury
by James T. Wassell 1275

A General Framework for Prioritizing Research to Reduce Injuries and Diseases in Mining
by Russell Levens 1285

Invited Papers:

I. Methodology
Lifetime Risk of Fatal Occupational Injuries Within Industries, by Occupation, Gender, and Race
by John R. Myers, Suzanne M. Kisner and David E. Fosbroke 1291

Estimates of Lifetime Risk of Occupational Fatal Injury from Age-specific Rates
by K. See and A.J. Bailer 1309

Years of Potential Life Lost Due to Occupational Fatal Injury in the United States
by Stephen J. Gilbert, A. John Bailer and Leslie T. Stayner 1321

Identifying Populations at High Risk for Occupational Back Injury with Neural Networks
by Douglas P. Landsittel, Lytt I. Gardner and Vincent C. Arena 1337

Relative Risk of Involuntary Injuries Among Currently Employed Adults in the U.S.
by Jai Won Choi, Ki Moon Bang and Robert A. Wright 1353

II. Special Worker Populations
Work-related Fatal Injury Risk of Construction Workers by Occupation and Cause of Death
by G-X Chen and D. Fosbroke 1371

Robbery-related Injury in Convenience Stores: Estimating Lifetime Risk and Identifying High Risk Populations
by Kimberly Faulkner, Douglas P. Landsittel 1391

Evaluation of Occupational Injuries Among Young Workers in West Virginia
by P. Simoyi, S. Islam, A. Haque, J. Meyer, E. Doyle and A. Ducatman 1405

Occupational Noise Sources and Exposures in Construction Industries
by Dale Hattis 1417

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