Injury Epidemiology: Fourth Edition

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Chapter 2. ENERGY CHARACTERISTICS AND CONTROL STRATEGIES

Injury epidemiologists should have at least a rudimentary understanding of the forms of energy involved in injury and the tolerance of human beings to exposure to energy. Since incidence and severity of injury is usually classified by vehicles or circumstances rather than by agent, the precise numbers attributable to a given agent in many available data sets is not available. At the turn of the century in the United States, about 58 percent of fatal injuries and 62 percent of hospitalized injuries were attributed to motor vehicles, falls and firearms (Finkelstein, et al., 2006). Although prescription drug induced deaths classified as poison have greatly increased in importance, as noted in Chapter 1, motor vehicles, guns and falls and a proportion of those injuries associated with factors and activities grouped into the "other" category (industrial machines, farm machines, knives, sports), indicates that mechanical energy accounts for the majority of severe injury.

Some energy releases, such as a nuclear explosion, include multiple forms of energy -- mechanical, heat, chemical and ionizing radiation. The acute effects of ionizing radiation have been rare and are not discussed in the following brief descriptions of common types of energy that cause the bulk of acute injuries.

MECHANICAL ENERGY. Mechanical energy, sometimes called kinetic energy, is the energy of motion. Any object, animate or inanimate, in motion at velocity substantially less than the speed of light, has energy in relation to its mass and speed that is described by a simple formula; energy equals mass times velocity squared, divided by 2:

$$K = mv^2/2 \qquad (1)$$

where K = energy in foot-pounds
m = mass
v = velocity in feet per second

A foot-pound is the energy needed to raise a pound of material one foot from the ground at the earth’s surface. Mass can be calculated at the earth's surface by dividing weight in pounds by 32. Velocity in miles per hour can be converted to feet per second by multiplying miles per hour by 1.467. Therefore, a 150 pound motor vehicle occupant traveling at 30 miles per hour has about 4,537 foot pounds of energy, calculated as follows:

$$[(150/32) \times 44^2]/2 = 4537.5$$

Increase in mass or speed increases the energy, speed obviously more so than mass because it is squared in the calculation. At 60 miles per hour (88 feet per second), the 150-pound vehicle occupant has about 18,140 foot-pounds of energy, twice the speed but about four times the energy at 30 miles per hour. If the person must stop suddenly, as an occupant of a vehicle in a crash, that energy must be dissipated in the vehicle, in the environment, or in the tissues of the individual. When the vehicle stops, the unbelted occupant will continue to move at the pre-crash speed into the interior structures, or into materials in the exterior environment if ejected. The load on the tissue is measured in pounds per square inch. The shape and elasticity of the materials struck will determine the damage to the tissue. Inflexible, protruding or pointed objects on dashboards, for example, will penetrate the heads or other parts of the anatomy of people who move into them in crashes at common traveling speeds in vehicles without energy absorbing cushions called air bags..

Devices such as child restraints, lap/shoulder belts, and air bags reduce the severity of injury by reducing contact with less flexible surfaces -- the so-called second collision. They also increase the uniformity of deceleration of occupant and vehicle, and spread the load over dozens of square inches. Energy absorbing materials, both in the vehicle and the environment, can also dissipate energy so that the individual's deceleration is less rapid (Yoganandan, et al., 2015). Helmets used by motorcyclists, bicyclists and in certain sports, as well as padding used in certain sports and on the hips of residents in certain nursing homes, also absorb energy if designed to do so.

The extent of damage to tissue is a function of the structure of the part of the body affected. Contact with an energy source generates forces counter to the load, called stresses. These constitute the resistance of the bonds among tissue molecules to deformation. The same tissue may have different capacity for tension stress (pulling molecules apart), compression stress (pushing molecules together), or shear stress (from a tangential force).

Strain refers to the extent of deformation and may be classified as resulting from tension, compression, or shear stress. Tissue varies as to elasticity -- the extent to which strain is eliminated when the load is removed -- and the regenerative capability of the organism (Stephenson, 1952). Nerves do not regenerate when severed and, therefore, injuries to the brain and spinal cord are especially disabling (Committee on Trauma Research, 1985). While a technological breakthrough in restoring nerve function may eventually occur, no reference was found that suggests it is likely to happen in the near future.

To the extent that the object striking or struck by human tissue is stressed more than the tissue, the energy will be transferred to the inanimate object and the human tissue will be damaged less. DeHaven's classic study of people who survived falls of up to 150 feet found no major injury in some cases where the deformation in the ground, car or other object struck was as little as a few inches (DeHaven, 1942).

With the exception of persons with diseases such as scurvy, osteoporosis, and hemophilia -- which reduce the elasticity of important tissues -- human beings are capable of experiencing substantial mechanical force with little or no injury if the load is not concentrated. Stapp conducted experiments with animals in rocket sleds and wind tunnels to test the limits of tissue tolerance and then tested healthy human volunteers, including him, within the estimated limits. Held in the sled only by three-inch-wide webbed harnesses over the shoulders and legs, and anchored to the sled, the volunteers experienced decelerations up to 35 g's with no damage and up to 45 g's with little damage (Stapp, 1957). A g is the measurement of gravity at the earth's surface, 32 feet squared per second. The effective weight of a

160-pound person decelerated at 35 g's is 5600 pounds. Yet, because the accompanying load was distributed over the surface of the restraining belts to reduce concentration at smaller points, and was partly absorbed by the belts, the test subjects sustained no serious injury.

Biomechanical engineers study the susceptibility of animate tissues to damage from mechanical energy loads. Materials engineers study the properties of matter that increase or decrease their energy absorbing capability. Experts in these fields should be consulted by epidemiologists who need information on the properties of tissue or other matter involved in a given set of injuries.

The velocity of the persons involved in an injury is often not known, but can be estimated using another formula from elementary physics (Bueche, 1977), velocity squared at time t equals velocity squared at time zero plus 2 times acceleration and distance moved:

$$v_t^2 = v_0^2 + 2ad \qquad (2)$$

where v=velocity in feet per second
t=time in seconds
a=acceleration
d=distance moved in feet

A person in a free fall accelerates at 32 feet per second every second (1 g). If we know the distance fallen, say 5 feet from the top of a sliding board in a playground, the velocity at impact can be calculated as follows from formula 2:

2

$v^2 = 0 + 2 \times 32 \times 5 = 320$

Therefore, the velocity at impact is the square root of 320, which is 17.9 feet per second. If we know the maximum weight of the children who use the sliding board, then we can calculate the energy at impact in the worst-case scenario, from the energy formula. Let's say the maximum weight of any child likely to climb onto the sliding board is 90 pounds. Then the energy that should be managed is:

$$[(90/32) \times 17.9^2] / 2 = 451 \text{ foot pounds.}$$

This, compared to the thousands of foot pounds of energy of the mentioned car occupant, should give more than a hint as to why motor vehicle injuries are, on average, more severe than fall injuries.

The surface under the sliding board could be designed to absorb more than 451 foot pounds of energy over a surface of a few square inches and no damage would occur to children who fall off. If playground builders were to conduct such calculations and compare the results to the energy absorbing properties of materials, they would find that the concrete or asphalt often placed under playground equipment does not do the job.

Faced with playground managers who do not believe the theoretical formula, an injury epidemiologist might use the basic physics to do a study of injuries in falls from playground equipment. The data to be collected would include severity of injuries, weight of the injured, height of the equipment used, and surfaces under the equipment. Using an appropriate statistical model, the data would be analyzed to examine the extent to which severity of injury is a function of the type of playground surface, controlling for the energy of the falling bodies.

Unfortunately, those who study such injuries usually do not collect the data needed to apply the physics to playground modifications. For example, a report that children's falls from playground equipment result in more serious injury than their falls from standing height (Fiissel et al., 2005) will surprise no one with common sense, much less those who know basic physics. No data on the height of the equipment or the surfaces contacted were included in the study. The National Safe Kids organization claimed on their website in 2006 that only 9 percent of playgrounds have energy absorbing material under equipment but cites no reference for the claim and no assessment of the adequacy of the material. A study comparing playgrounds where hazardous equipment was removed or replaced to playgrounds not yet modified found that injuries declined about a third on playgrounds with the modifications (Howard, et al., 2005).

The severity of the second leading cause of fatal mechanical injury, gun-related injury, is also substantially a function of the characteristics of the involved vehicles of the energy -- guns and bullets. In addition to high velocity applied to less than a square inch of body surface in most cases, which results in frequent deep penetration of vital organs, the extent of fragmentation after penetration increases the damage to organs affected. Muzzle velocities of bullets range widely, from 1200 to 2700 feet per second. They generate energy from 93 to 8092 foot- pounds at close range (Karlson and Hargarten, 1997).

Bullets used by military forces are required by the Geneva Convention to be fully jacketed and retain their approximate original shape while moving through human tissue. Bullets sold in the United States for domestic use do not meet such a standard. Their sometimes-blunt ends and frequent fragmentation result in wounds that have an average size twenty-seven times those caused by military bullets (DeMuth, 1966). Yet epidemiologists often study gun-related injuries as if all guns and bullets were the same.

CHEMICAL AND THERMAL ENERGY. Chemicals may be breathed, ingested, injected or absorbed. Most fatal injuries from chemical poisoning are from ingested prescription opioid drugs, a legal form of opium if prescribed by a medical professional. The effect of chemical exposure is a function of the concentration of the exogenous chemical, its interaction with body chemistry, and the rapidity of elimination relative to individual susceptibility. The dose-response curve may also vary based on genetic susceptibility, physiological development, increased or reduced tolerance resulting from previous exposure, and presence or absence of other chemicals that can have synergistic effects (McQuay, 1999)..

Toxicologists divide the process of harm by a chemical into three phases -- exposure, toxokinetic, and toxodynamic. Epidemiologists have paid some attention to the first of these in the study of poisonings, but the second and third deserve attention regarding severity. The toxokinetic phase refers to the chemical's absorption through the organism's membranes, usually in the alimentary canal or the lung sacs in the case of common poisonings, as well as the distribution, metabolism, and excretion in the vascular and waste disposal systems. The interaction of the chemical with receptors in target tissues constitutes the toxodynamic phase (Ariens, et al., 1976). See http://sis.nlm.nih.gov/enviro/toxtutor.html for tutorials on toxicology. Researchers have given some attention to the possibility of reduction of the effects of alcohol and narcotics in the toxodynamic phase based on increased understanding of receptors, but less attention has been given to the toxokinetic phase. For example, suggestions that something could be added to alcohol to reduce absorption in the alimentary canal or make the drink taste bad after a couple have been consumed (Robertson, 1981) is often greeted with the statement that people would just drink more. Perhaps some would, but many people in the process of "partying" likely do not pay attention to the amount consumed. The issue deserves empirical research rather than offhand dismissal.

Some effort has been made to change the formulation of opioid drugs to prevent tablets or capsules being crushed to form injectable substances. The research indicating major effectiveness is based on self-reports (Cicero et al, 2012) and reports to the manufacturer (Sessler, et al, 2014) that may be unreliable. Analysis of insurance claims suggests that heroin overdoses increased somewhat during the time of the reduction in prescription drug overdoses (Larochelle, et al., 2015) but such data cannot specify that the prescription drug users switched to heroin.

The deaths and injuries associated with fires, heat and smoke are the result of use of ignition sources and flammable materials, and the heat and chemical energies generated by burning or heating materials. The most common ignition source in fatal fires is a cigarette dropped in furniture or bedding, often smoldering until the occupants of a household are asleep. The extent to which a cigarette will continue to burn when dropped is a function of type of tobacco, tobacco density, paper porosity, citrate added, circumference, and second paper wrapping

(Technical Study Group, 1987). Other ignition sources deserving of epidemiological attention as to variations leading to fire ignition are matches, cigarette lighters, gas stoves, and electrical circuits or appliances. Heat from sources other than ignited fires most often include heated water and other liquids, heating units on stoves, and space heaters.

The physics and chemistry of combustion vary according to several factors: 1. concentration and type of heat source, 2. shape and size of a combustible, 3. oxygen concentration, 4. vaporization of gasses, and 5. presence or absence of catalysts (National Fire Protection Association, 2008). Heat is transferred among solids, liquids and gasses, in proximity to one another, from the medium at higher temperature to the medium at lower temperature. The effect of heat on human tissue is a function of the temperature and the time of exposure (Moritz and Henriques, 1947, Karter, 2005).

ELECTRICAL ENERGY. Electrical energy is inherent in matter. Atoms are made up of electrons (negatively charged), protons (positively charged), and neutrons (neutrally charged). Gain or loss of electrons in orbit about the nucleus determines whether the atom is positively or negatively charged. The flow of electrons is electrical current. The atoms of different materials, including human tissues, vary in their tendency to hold an electrical charge.

The term amperes refers to electrical current flow in a unit of time and varies as a function of the electromotive force (volts) divided by resistance to conductivity (ohms) that characterizes the materials and situation involved. The extent of damage to human tissue in contact with electrical energy increases with amperage. Muscular paralysis occurs at about 0.02 amperes, ventricular fibrillation at 0.10 amperes, and ventricular paralysis at 2.0 or more amperes.

Skin resistance varies one hundred fold as a function of wetness -- 100,000 ohms when dry but 100 ohms when soaked. The water serves as a low resistance conductor if the water is in contact with the ground. Thus, a 120-volt electrical current in the average home socket will have low amperage (0.001) in contact with dry skin, but will be high enough (0.12) to cause ventricular fibrillation if the skin is soaking wet and in contact with the ground. Deaths attributed to heart failure or other causes are sometimes found upon detailed examination to have been caused by electricity (Wright and Davis, 1980). Clinical management of those who survive is difficult (Teodoreanu, et al., 2014).

ASPHYXIATION. The human organism cannot function with too little energy. The absence of oxygen to sustain endogenous energy conversion, called asphyxiation, causes essential cells in the brain and heart to be damaged within minutes. Asphyxiation can occur from objects or other material blocking the nose and mouth or trachea (e.g., by a plastic bag or balloon fragment), a mechanical blow to the trachea (e.g., by a "karate chop" dash board tapered toward the occupant in a car crash), constriction of the trachea (e.g., hanging by a rope), or obstruction in the lungs. The most common fatal form of asphyxia from acute exposure to external sources, counted as injury, is water in the lungs, usually labeled as drowning or near drowning. Lung congestion from endogenous fluids, as in pneumonia and congestive heart failure, is attributed to diseases.

TECHNICAL CONTROL STRATEGIES. Similar to cancer epidemiology and control, the varieties of energy sources involved in injury and the differences in populations exposed to the various types of energy mitigates against a single cure for the whole problem. In contrast to cancer, however, one does not have to wait years to find out if a given control strategy is having an effect on the subset of injuries toward which it is targeted.

William Haddon, Jr. (1970) defined 10 logically distinct technical strategies for injury control as well as reduction of harm from all hazards. He recommended that analysts consider the broadest range of possible strategies before considering feasibility of implementation. The following is a list of the strategies, with examples relevant to some of the more commonly severe injuries:

1. Prevent the creation of the hazard in the first place. Do not manufacture particularly hazardous vehicles, such as motorcycles, mini-bikes, and "all terrain" vehicles. These vehicles are used mainly for recreation, for which there are numerous substitutable less hazardous activities. Do not manufacture addictive drugs.

2. Reduce the amount of the hazard brought into being. Require that passenger vehicles have lower centers of gravity or wider track width such that track width divided by twice the height of center of gravity (T/2H) is not less than 1.2. Vehicles with lower T/2H have 3 to 20 times as many fatal rollover crashes as those 1.2 or greater and the relative risk is strongly correlated to T/2H. Require that all motor vehicles operated on a level surface be incapable of speeds greater than 65 miles per hour. (Limitations on maximum speed would also conserve fuel and reduce emissions.) Allow sale of handguns only to police and military units. Reduce the number of pills in a prescription for drugs to a number that would not kill or disable if taken all at once. Reduce flammability of clothing. Reduce maximum temperature capability of hot water heaters, the source of heat for many scald burns.

3. Prevent the release of the hazard that already exists. Improve braking capability of motor vehicles, especially heavy trucks and SUVs that have longer braking distances than cars. Keep guns for target shooting at the shooting range rather than in homes. Provide canes and walkers to the elderly and handrails in their environments. Make matches and lighters less easy for children to ignite.
4. Modify the rate or spatial distribution of release of the hazard from its source. Use child restraints and seat belts in motor vehicles. Prohibit automatic and semi-automatic guns. Use lightly woven and smoothly finished fabrics in clothing to reduce burning rates. Install automatic sprinkler systems in buildings. Provide systems that replace air rapidly in passenger compartments of motor vehicles to prevent elevated carbon monoxide concentrations.
5. Separate, in time or space, the hazard and that which is to be protected. Remove trees and poles from near roadsides. Build pedestrian and bicycle paths separated from roads. Place children in the back seat of motor vehicles. Prohibit large truck traffic, especially if transporting flammables or toxic chemicals, during periods of congestion. Restrict hunting and target shooting to unpopulated areas. Evacuate coastal areas at times of approaching hurricanes. Use cooking units that children cannot reach or keep children out of the kitchen while cooking.
6. Separate the hazard and that which is to be protected by interposition of a material barrier. Increase energy absorbing capability of vehicle exteriors. Install air bags in passenger vehicles. Require motorcyclists and bicyclists to use helmets. Use energy absorbing barriers on the fronts and rears of large trucks that are compatible with car bumper heights. Install energy absorbing barriers between roads and bridge abutments or other necessary rigid structures near roads.

Place fences with gates that children cannot open around swimming pools and other small bodies of water in areas where children can reach them. Place guards on boat propellers, industrial machines and the like where moving parts can injure those in proximity. Use insulated firewalls in vehicles and buildings. Invent an additive to alcoholic beverages and other commonly ingested drugs that reduce absorption through the wall of the digestive track into the bloodstream as increasing amounts are ingested.

7. Modify basic relevant qualities of the hazard. Eliminate sharp points and edges on vehicle exteriors. Eliminate protruding knobs and "karate chop" dashboards in vehicle interiors. Use breakaway designs for utility poles and light poles along roadsides. Prohibit more than one trailer on tractor-trailer rigs. Reduce muzzle velocity of guns. Use trigger locks on guns. Apply to ammunition sold to the public the Geneva Convention regulation that prohibits flattening and fragmenting of bullets used in war. Use energy-absorbing materials of adequate depth on playground surfaces and floors of elderly housing.

8. Make what is to be protected more resistant to damage from the hazard. Develop treatment of persons with hemophilia and osteoporosis to increase resistance to mechanical energy exchanges. Require physical conditioning before participation in sports that produce condition-related injuries.

9. Begin to counter the damage already done by the environmental hazard. Increase the availability of roadside emergency telephones. Place emergency response teams near areas with relatively high injury rates. Increase use of smoke detectors and carbon monoxide detectors.

10. Stabilize, repair and rehabilitate the object of the damage. Provide prosthetic devices for amputees and wheelchairs,

beds, and equipment used in work and other activities designed to optimize normal living. Provide job and self-care training.

Too often these strategies, or reference to them, are missing from published articles and books on injury control. The commonly cited Haddon Matrix is widely used to illustrate the factors and phases but the 10 strategies are far more important in the systematic consideration of possible countermeasures.

The adoption of any one strategy is dependent on various aspects of inventiveness, ideology, politics and costs. Epidemiologists can play a central role in pinpointing energy exposures, incidence and severity among particular populations, and evaluation of the effectiveness of injury control strategies. Costs of injury control can be minimized by application of the strategies to agents, vehicle or vectors, hosts and environments in which the severity of injuries and their associated costs are most acute.

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