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Perspective

Organ Donation after Cardiac Death

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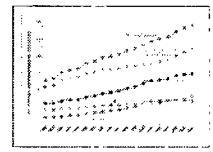
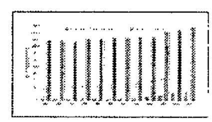
Article

Although the numbers of organ donors and transplantations in the United States have more than doubled over the past 20 years (see line graph), the demand for organs continues to dwarf the supply. In 2006, there were about 29,000 solid-organ transplantations; as of June 2007, there were about 97,000 people on waiting lists for organ transplantation.



Organ Donors and Transplantations in the United States, 1988–2006.

About three of every four organs that are transplanted are recovered from deceased donors. The most rapid increase in the rate of organ recovery from deceased persons has occurred in the category of donation after "cardiac death" — that is, a death declared on the basis of cardiopulmonary criteria (irreversible cessation of circulatory and respiratory function) rather than the neurologic criteria used to declare "brain death" (irreversible loss of all functions of the entire brain, including the brain stem). Organs were recovered from 645 donors after cardiac death in 2006, as compared with 189 in 2002; these donors accounted for 8% of all deceased donors in 2006 (see bar graph). At the Organ Procurement Organization at the University of Wisconsin, the New England Organ Bank in the Boston area, and the Finger Lakes Donor Recovery Network in New York, such donors accounted for more than 20% of all deceased donors.



Distribution of Deceased Organ Donors in the United States, 1995–2006.

Since 1968, when an ad hoc committee at Harvard Medical School proposed a brain-based definition of death that became widely accepted, organs for transplantation have been removed primarily from hospitalized patients who have been pronounced dead on the basis of neurologic criteria, when they are on ventilators and their hearts continue to function. The continued circulation of blood helps to prevent the organs from deteriorating.

Obtaining organs from donors after cardiac death — when the heart is no longer beating — is the approach that was generally followed in the 1960s and earlier. Today, such donations typically involve patients who are on a ventilator as the result of devastating and irreversible brain injuries, such as those caused by trauma or intracranial bleeding. Potential donors might also have high spinal cord injuries or end-stage musculoskeletal disease. Although such patients may be so near death that further treatment is futile, they are not dead.

The United Network for Organ Sharing, a private nonprofit group based in Richmond, Virginia, operates the Organ Procurement and Transplantation Network under contract with the federal government and is committed to increasing the number of donors. OPTN/UNOS, as the networks are collectively known, has developed rules for donation after cardiac death. According to these rules, finalized in March 2007, the process begins with the selection of a suitable candidate and the consent of the legal next of kin to the withdrawal of care and retrieval of organs. Subsequently, life-sustaining measures are withdrawn under controlled circumstances in the intensive care unit (ICU) or the operating room; donation after an unexpected fatal cardiac arrest is rare.

When the potential donor meets the criteria for cardiac death, a doctor pronounces the patient dead. The time from the onset of asystole — the absence of sufficient cardiac activity to generate a pulse or blood flow (not necessarily the absence of all electrocardiographic activity) — to the declaration of death is generally about 5 minutes, but it may be as short as 2 minutes.[1] The limited data available suggest that circulation does not spontaneously return after it has stopped for 2 minutes.[2] The organs

— most commonly the kidneys and liver but also the pancreas, lungs, and, in rare cases, the heart — are then recovered. To avoid obvious conflicts of interest, neither the surgeon who recovers the organs nor any other personnel involved in transplantation can participate in end-of-life care or the declaration of death.

The outcomes for organs transplanted after cardiac death are similar to those for organs transplanted after brain death. However, the length of time varies as to which organs can be deprived of oxygen (the interval from cessation of circulation to the initiation of perfusion with cold preservation solutions) and still be transplanted successfully. It is best to retrieve the liver less than 30 minutes after the withdrawal of life-sustaining measures; the kidneys and pancreas may often be recovered up to 60 minutes after such withdrawal.[1] The extent of a patient's remaining circulatory and respiratory function may reveal whether death is likely to follow soon after extubation. If a patient does not die quickly enough to permit the recovery of organs, end-of-life care continues and any planned donation is canceled. At present, this may happen in up to 20% of cases.

In 1997, 2000, and 2005, the Institute of Medicine reviewed and voiced support for donation after cardiac death.[3] In 2005, a conference on donation after cardiac death concluded that it is "an ethically acceptable practice of end-of-life care, capable of increasing the number of deceased-donor organs available for transplantation."[1] Nonetheless, some physicians and nurses at the bedside "continue to have concerns about the ethical propriety of the practice" that "are numerous, complex and related to the specific roles they play."[4] Some feel uncomfortable about participation in medical practices that may be required during the transition from end-of-life care to organ donation.[5] For example, in multidisciplinary ICUs, doctors and nurses who care for both potential organ donors and organ recipients may have conflicting interests. They may be uncomfortable recommending the withdrawal of life-sustaining treatment for one patient and hoping to obtain an organ for another.

According to the "dead donor rule," donation should not cause or hasten death.[3] As currently practiced, donation after cardiac death inevitably raises more concerns than donation after brain death. The process is more complex, and the potential donor is not dead when life-sustaining measures cease. The intervals between withdrawing care, pronouncing death, and recovering organs are very brief, and the family's relation to the dying process may be affected. In an interview, Sue McDiarmid, a professor of pediatrics and surgery at the University of California, Los Angeles, and the immediate past president of OPTN/UNOS, said, "The perception of some physicians and families is that the end-of-life experience is changed because organ procurement begins immediately after death has occurred. However, many families find great solace in the ability to donate organs under these special circumstances."

Concerns were raised by a February 2006 case in San Luis Obispo, California, that was publicized earlier this year by the *Los Angeles Times*. Two transplant surgeons were allegedly in the same room with a potential donor, and one of the surgeons allegedly ordered massive doses of morphine and lorazepam in an attempt to hasten the patient's death and thereby obtain his organs more quickly. The patient did not die for several hours, and his organs were not recovered because they were no longer usable for transplantation. The case, which has been investigated by local law-enforcement authorities, is a sobering reminder that organ-donation efforts can go terribly wrong if appropriate procedures are not followed.

Typically, potential donors are wheeled to the operating room when they are still alive. With explicit consent, heparin — possibly along with other agents — is administered to maintain organ function. According to the 2005 Institute of Medicine conference, providing heparin at the time of withdrawal of life-sustaining treatment "is the current standard of care" because "the long-term survival of the transplanted organ may be at risk if thrombi impede circulation to the organ after reperfusion."[1] Theoretically, heparin could hasten death by causing bleeding, but there is no evidence that it does so in practice. Some protocols also call for the advance placement of catheters in large arteries and veins to facilitate the rapid infusion of organ-preservation solutions after death.[1]

In January 2007, the Joint Commission (formerly the Joint Commission on Accreditation of Healthcare Organizations) implemented its first accreditation standard for donation after cardiac death. According to this standard, hospitals with the necessary resources must develop donation policies in conjunction with their medical staff and their organ-procurement organization that address "opportunities for asystolic recovery" of organs. Since many hospitals have never had an organ donor whose death was declared on the basis of cardiopulmonary criteria, meeting the standard may require new approaches to both organ donation and end-of-life care. The standard, however, requires that relevant hospitals have the policies in place, not that they allow the practice — they can choose to opt out because of concerns about ethics, quality of end-of-life care, or other reasons. When a hospital and its medical staff decide not to provide for donation after cardiac death and the organ-procurement organization is not in accord, the hospital must document its efforts to reach an agreement and include in the donation policy its justification for opting out. In addition, as of July 1, 2007, OPTN/UNOS has required all 257 transplant hospitals and 58 organ-procurement organizations in the United States to comply with its new rules.

If the number of organ donations after cardiac death continues to increase, more patients will be able to receive transplants. At present, however, these donations remain troubling to some and are not as widely accepted as donations after brain death.[4,5] Broader experience with the recommended practices should help, but concerns are likely to persist.

All organ-procurement organizations and transplant centers in the United States must develop and comply with protocols to facilitate the recovery of organs from donors after cardiac death, according to the Organ Procurement and Transplantation Network and the United Network for Organ Sharing (known collectively as OPTN/UNOS). Listed here are "model elements" that the protocols are required to address, as adopted by the OPTN/UNOS board of directors in March 2007; they became effective on July 1, 2007.

"A patient . . . who has a non-recoverable and irreversible neurological injury resulting in ventilator dependency but not fulfilling brain death criteria may be a suitable candidate for donation after cardiac death. Other conditions [may] include end stage musculoskeletal disease, pulmonary disease, and high spinal cord injury."

"The decision to withdraw life-sustaining measures must be made by the hospital's patient care team and legal next of kin, and documented in the patient chart." Depending on the circumstances, the "legal next of kin" may be a relative, a designated health care representative, or an appropriate surrogate.

The assessment of potential donors "should be conducted in collaboration with the local organ procurement organization and the patient's primary health care team." The medical director of the organ-procurement organization and transplant-center teams may be consulted.

"An assessment should be made as to whether death is likely to occur (after the withdrawal of life-sustaining measures) within a time frame that allows for organ donation."

The legal next of kin may consent to the administration of drugs, such as heparin, or procedures, such as the placement of femoral catheters, for the purposes of organ donation. "No donor related medications shall be administered or donation related procedures performed without consent."

Clearance from the medical examiner or coroner "must be obtained when applicable." There should be plans for continued end-of -life care and immediate notification of the family "if death does not occur within the established timeframe after the withdrawal of life-sustaining measures."

"A surgical timeout is recommended prior to the initiation of the withdrawal of life-sustaining measures." The intent is to verify patient identification and the roles and responsibilities of the various personnel.

"No member of the transplant team shall be present for the withdrawal of life-sustaining measures," such as removal of an endotracheal tube or termination of medications for blood-pressure support. "No member of the organ recovery team or organ procurement organization staff may participate in the guidance or administration of palliative care, or the declaration of death."

If applicable, placement of femoral catheters and the administration of heparin or other pharmacologic agents "for the sole purpose of donor organ function must be detailed in the consent process."

"The patient care team member that is authorized to declare death must not be a member of the organ procurement organization or organ recovery transplant team. The method of declaring cardiac death must comply in all respects with the legal definition of death by an irreversible cessation of circulatory and respiratory function *before* the pronouncement of death."

"Following the declaration of death by the hospital care team, the organ recovery may be initiated."

"Organ procurement organization policy shall be to ensure that no donation related charges are passed to the donor family."

An interview with Francis Delmonico, chief of transplant services at Massachusetts General Hospital and medical director of the New England Organ Bank, and Michael Grodin, professor of health law, bioethics, and human rights at the Boston University School of Public Health can be heard at www.nejm.org.

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Structure Fires, Smoke Production, and Smoke Alarms

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Smoke inhalation injury causes severe morbidity and death. In the United States, the majority of fatalities from fire and burns occur because of inhalation of smoke. Medical treatment is only supportive; there is no known antidote to the damaging effects of smoke toxicants on pulmonary tissue. Without question, minimization of the morbidity and mortality that are caused by smoke inhalation is best accomplished by prevention of the injury. Effective prevention programs depend on a thorough and detailed understanding of the mechanism of damage caused by smoke, as well as of the available options for efficacious prevention. This summary presents details of smoke production from structure fires, the effects of smoke on physiology, and the devices currently in use to prevent damage and death from smoke. (J Burn Care Res 2011;32:511–518)

STRUCTURE FIRES AND SMOKE PRODUCTION

The products of combustion consist of fire gases, heat, visible smoke, and toxicants. The hazards created by these products of combustion include effects of heat on the upper airway, toxicant damage to the subglottic respiratory system, impaired vision due to smoke density or eye irritation, and narcosis from inhalation of asphyxiants. These effects contribute to restricted vision, loss of motor coordination, impaired judgment, disorientation, physical incapacitation, and panic. The resultant delay or prevention of escape from the burning structure leads to injury and death from inhalation of toxic gases and from thermal burns. Extricated survivors may later die in the hospital from complications such as respiratory failure, septic shock, and multiple organ system failure, all of which are rooted in the initial exposure to products of combustion.[1]

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In the United States, the majority of fatalities from fire and burns occur because of inhalation of smoke.[2] Smoke is defined as the airborne solid and liquid particulates and fire gases created during combustion and when materials undergo decomposition or transformation by heat.[3] Pyrolysis is the decomposition of a material from heat; because it does not require the normal atmospheric level of oxygen that would allow the fuel to react completely to produce carbon dioxide and water, it leads to incomplete combustion. The toxicant gases produced in a fire can be categorized into separate classes: the asphyxiants that induce unconsciousness and the irritants that inflame the eyes and respiratory tract. The major threat in most fire atmospheres is carbon monoxide, an asphyxiant produced by incomplete combustion.

In the United States each year, the vast majority of deaths due to fires occur because of exposure to products of combustion in structure conflagrations. From 1992 to 2001, two thirds of fire deaths in the United States occurred in residential fires.[1] (Although residential fires are the primary cause of fire mortalities, they account for only half of structure fire injuries and less than one third of the dollar loss for fires.) Residential fires accounted for 76% of the years of life lost in 2006 in the United States due to flame burns.[4]

Although most victims of fatal fires die from smoke inhalation, a few will die directly from thermal injury. Temperatures higher than 300°F are reached within 5 to 10 minutes in building fires.[5] The temperature inside a burning aircraft may rise very quickly; in one test, a temperature of 1093°C was reached in less than 2 minutes.[6] Flashover is defined as a transitional phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space resulting in full room-involvement or total involvement of the compartment or enclosed area.[7] Flashover can occur in less than 10 minutes even in a slowly progressing residential fire, at which time temperatures soar from 1100°F to >2000°F in seconds, creating an environment in which survival is rare. In the absence of inhalation of the products of combustion and pyrolysis, death can be caused by heat-induced laryngospasm or by vagal reflex-mediated cardiac arrest.[8]

Carbon monoxide (CO) is produced from the incomplete combustion of carbon-containing compounds and resultant CO poisoning is another danger in structure fires. A well-ventilated fire will produce much more carbon dioxide than CO, but most structure fires smolder due to the consumption of oxygen in the interior of the building, even when ambient oxygen is reduced to half its normal volume in the air. CO poisoning is characterized by headaches, confusion, visual changes, nausea and vomiting, dizziness, and disorientation. Higher exposure levels lead to tachypnea, tachycardia, seizures, coma, and eventually death. The symptoms are often nonspecific and may be confused with other diseases such as acute respiratory distress syndrome, lactic acidosis, acute alcohol inebriation, and opioid intoxication, all of which may present in victims of structure fires.[9]

Although the pathophysiology of CO poisoning is well understood, there remains no readily apparent explanation for the observation that carboxyhemoglobin (COHb) is tolerated over a very wide range. Although COHb saturation >35% can cause death in some people, others have survived COHb saturations as high as 64%.[1] The average COHb level in fire fatalities is 60%, with a range of 25 to 85%.[7] About 10 to 15% of CO binds to myoglobin and cytochrome A3, blocking production of ATP and causing muscular weakness, thus exacerbating the difficulties the victim encounters during escape maneuvers.[10]

Unfortunately, COHb levels rise rapidly in house fires. When the CO level in inspired air reaches 5%, COHb rises to 10% in 10 seconds and to 40% (a fatal level in some people) in only 30 seconds.[11] A study in East Denmark from 1982 to 1986 demonstrated that the blood alcohol concentration averaged about 190 to 200 mg/dl in fatalities from residential fires, and the mean COHb was about 60%.[12] However, it is clear that some people with pre-existing functional impairments are at risk for increased CO toxicity at lower COHb levels, including children and the elderly; the physically disabled; and those impaired by alcohol, drug, or medication intoxication.[13,14] Largely for this reason, children younger than 5 years and the elderly older than 65 years account for 45% of home fire deaths.[15] Patients with coronary artery disease cannot increase coronary blood flow when COHb rises above 10%.[16] In addition to inhibiting cognitive responses, ethanol also potentiates the effects of CO such that lower levels of COHb are associated with fatality.[17]

Hydrogen cyanide (HCN) gas is produced by the combustion of materials that contain nitrogen, such as wool, silk, acrylonitrile polymers, nylons, and polyurethanes. Inhibition of cellular cytochrome C oxidase leads to an inability of the mitochondria to employ oxygen for respiration. The signs and symptoms of HCN poisoning are very similar to those of CO poisoning. Symptoms of low levels of HCN poisoning include weakness, headaches, confusion, and tachypnea; higher levels lead to seizures, coma, apnea, cardiac arrest, and death. The differential diagnosis of cyanide toxicity includes acute coronary artery syndrome and myocardial infarction, anxiety disorder, and metabolic acidosis.[18] Although HCN is 20 times more toxic than CO, HCN's role as a causative agent in human fire fatalities is less clear than that of CO. For example, in many fire deaths, COHb is in the toxic range, but cyanide levels are not toxic.[19] Nonetheless, low levels of COHb in other fire fatalities suggest that other toxic gases such as HCN may play a role in causing death.[20]

A rapidly spreading fire consumes oxygen and competes with the building inhabitants for the available oxygen. Because oxygen is consumed during combustion, the oxygen level in the inspired air (O_2) can drop from 21% to levels that affect coordination, mentation, and consciousness. When O_2 drops to 17%, coordination is impaired; when it drops to 14%, judgment becomes faulty; and below 6%, unconsciousness occurs.[1] Even though a fire may still smolder at 12% ambient oxygen, a house fire is an oxygen-deficient atmosphere, resulting in hypoxia and acidemia in smoke inhalation patients.

Acrolein, formed from the smoldering of all plant materials (including wood and the natural fibers used in decorations and furnishings), is a potent sensory and pulmonary irritant. It is extremely irritating to the eyes at concentrations as low as a few parts per million.[21]

Level of consciousness and thus ability to escape are affected by drugs and alcohol.[20] One third to one half of victims of fatal fires have ingested alcohol.[22–24] Ethanol intoxication significantly impairs the ability to escape from fire and smoke and is a contributory factor in smoke-related mortality. While victims found near escape exits had blood alcohol levels (BALs) averaging 88 mg/dl, the mean BAL was 268 mg/dl in those found dead in bed, presumably having made no attempt to escape.[25] Moreover, if even one person in the house is impaired by alcohol or drug use, others in the dwelling are also at increased risk of death from fire.[26]

Perhaps the most deadly combination leading to fatal fires is alcohol and cigarettes. Smoking in bed while inebriated is one of the most common causes of death by fire in North America, not only in higher socioeconomic neighborhoods but also in indigenous communities. In Canadian Indians in Manitoba and Alberta, 76 and 90%, respectively, of the adult victims of residential fires were under the influence of alcohol at the time of death.[27,28]

Risk factors for fatal and nonfatal house fire injuries include young or old age, male gender, non-white race, low income, disability, smoking, and alcohol use.[29] Single, detached mobile homes had the highest rate of fire deaths of all types of residences.[29] In rural areas, the risk of death from a residential fire in a mobile (manufactured) home is 1.7 times the risk in a single- or multiple-family home.[26] In addition, the presence of an able-bodied adult who is not impaired by alcohol or drugs will significantly increase the odds of survival in a house fire.[30] Burn injuries and fire fatalities are more common in older homes and from fires started in the bedroom or living room from heating equipment, smoking, or children playing with fire.[14]

SMOKE DETECTORS AND ALARMS

During combustion, the combined hazards of heat and smoke intensify over time to a point at which environmental conditions are incompatible with life. Between the time that the fire is discovered and the critical time at which point escape is impossible, a window of time occurs during which actions can be taken to minimize or prevent injury. The role of early detection systems is to lengthen this interval. (In some cases, when sleeping or intoxicated victims are overcome by hypoxia and CO poisoning, there is effectively no interval of time for action.) Data from the United Kingdom, which tracks the interval between the time of ignition and the time of discovery, confirm that smoke alarms result in quicker fire discovery. In home fires in which alerts were sounded by a smoke alarm, 63% were discovered within 5 minutes of ignition, and the fire was confined to the item of origin in 62% of these incidents.[31]

Early detection systems include different types of fire warning equipment such as sprinklers and devices that detect heat or smoke. Photoelectric detectors pass a beam a light above a sensor. Under normal conditions, the light beam passes above the sensor with no deflection of light to the sensor, which is positioned at 90° from the light beam. However, when smoke particles in the air cause some of the light to scatter, some of the light is dispersed to the sensor, which then triggers the alarm. Photoelectric alarms respond sooner to fires that begin with a long period of smoldering without flames. Ionizing detectors contain a small amount of Americium-241, which emits alpha particles. The Americium ionizes the oxygen and nitrogen in the air of the ionization chamber, causing a small current to flow between the two plates in the chamber. The presence of smoke in the chamber disrupts this current flow, which is then detected and triggers the alarm. Ionizing detectors respond quickly in flaming fires. From 1977 to 1982, there was rapid increase in the number of homes protected by smoke alarms, followed by a slower but continual rise in installation through 1993. Although the prevalence of usage has leveled since then, 96% of households surveyed by telephone reported having at least one working smoke alarm.[32,33] The death rate per 100 reported home structure fires from 2003 to 2006 in the United States was twice as high when no working smoke alarm was present (ie, either no smoke alarm was present or an alarm was present but did not operate) compared with the rate with working smoke alarms (1.16 vs 0.59). Having a working smoke alarm cuts the chances of dying in a residential fire in half.[34]

Inversely correlating with the rise in usage of smoke detectors has been the decline in residential fire and flame deaths. The age-adjusted death rate in 1981 from residential fires was 2.28; by 1997, that rate was reduced by almost 50%[4] (Figures 1 and 2). Although smoke alarms have contributed significantly to this reduction in mortality, other factors have been beneficial as well, including safer heating and cooking appliances; child-resistant lighters; flame-resistant mattresses, furniture, and clothing; and improvement in acute care of burn victims.

Many states and the District of Columbia have passed legislation that require smoke alarms be installed in both new and existing buildings. Other states have laws regarding specific conditions, such as new home construction, multi-family dwellings, or rental properties. In addition to legislation, policies dictated from governmental organizations protect consumers from other factors contributing to fire risk. One mandate for manufacturing has involved the safety features of disposable and novelty cigarette lighters. Since 1994, when the U.S. Consumer Product Safety Commission published

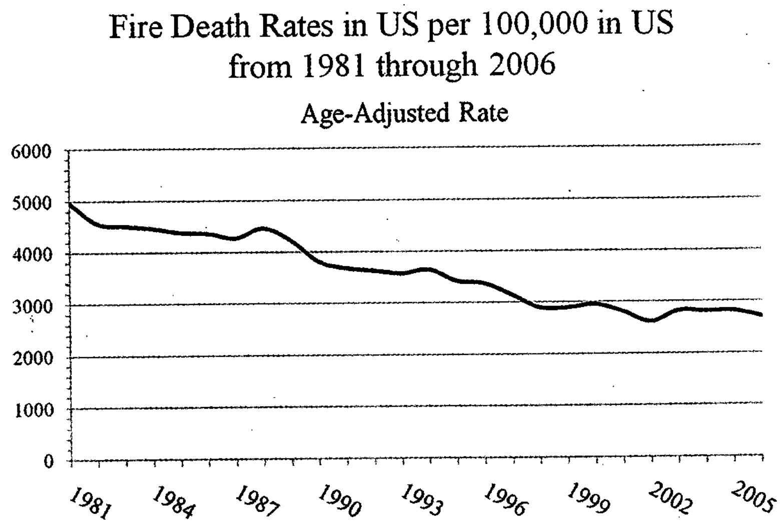

Figure 1. Deaths from fire and burns in the United States have declined from a rate of 2.99 per 100,000 population in 1981 to 1.2 per 100,000 in 2006, according to the Web-based Injury Statistics Query and Reporting System of the Centers for Disease Control and Prevention (http://webappa.cdc.gov/sasweb/ncipc/mortrate.html).[4] Residential fire deaths cause the majority of deaths due to fire and burns in the United States, ranging from 70 to 80% each year from 1981 through 2006. Age-adjusted death rates from residential fires declined an average of 20% every 5 years from 1981 to 1991. Recent reductions in residential fire death rates have been less remarkable, with only a 10% decrease from 2001 to 2006.

a safety standard requiring these lighters be made child-resistant, burn injuries and deaths have decreased 26 and 31%, respectively.[35]

The efforts to promote smoke detectors are best combined with accompanying educational efforts so that building occupants develop and rehearse escape plans in advance. Likewise, plans should address whether ancillary devices such as escape ladders might be necessary.[14] Installing, testing, and maintaining smoke alarms are critical for protection from a resi-

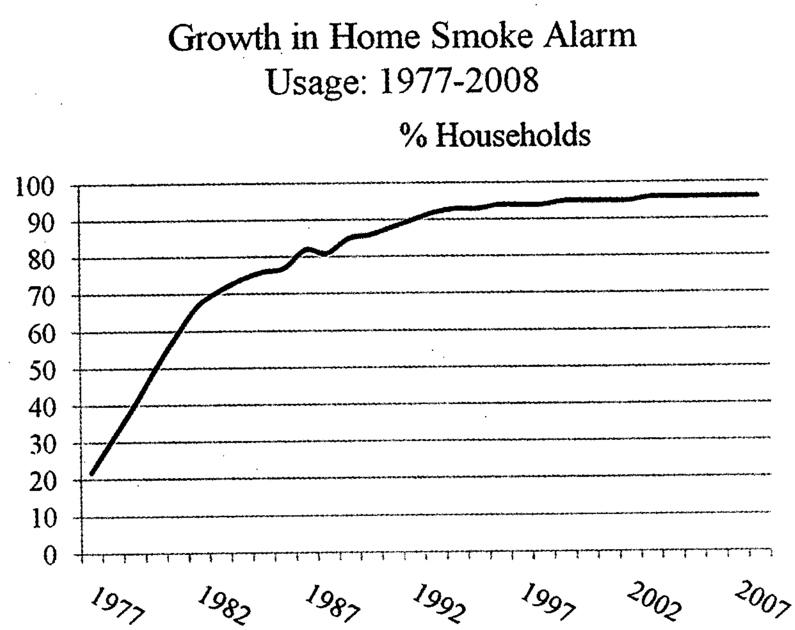

Figure 2. The use of home smoke alarms burgeoned from 1977 to 2008. A study that collected data via telephone for the National Fire Protection Association reported that by 2008, 96% of all homes surveyed had at least one smoke alarm.[32] A comparison of Figure 1 with Figure 2 shows the inverse relationship between the growth in use of home smoke alarms and the reduction of residential fire deaths in the United States over the same period.

dential fire, but they are not enough. A smoke alarm merely sounds the warning, but it cannot by itself remove people from harm. Unfortunately, many households have not developed the escape plans that would allow them to use to best advantage the extra warning time that smoke alarms provide. Escape plans will identify obstacles to secondary exits if the main door is blocked; establish a meeting place outside the home for household members to gather; and make provisions for disabled, young, or old household members.[34]

Almost two thirds of home fire deaths result from fires in properties without sounding smoke alarms. Between 2003 and 2006, smoke alarms were present in roughly two thirds (69%) of reported home fires and sounded in roughly half (47%) of the home fires reported to U.S. fire departments. Forty percent of home fire deaths resulted from fires in which no smoke alarms were present at all. Twenty-three percent of the deaths were caused by fires in properties in which smoke alarms were present and but failed to operate.[34]

Despite the dissemination of smoke detectors into homes, results have been disappointing. In 2006, for example, 2704 people died from residential fires.[4] Although the death rate in residential fires is doubled if smoke alarms are either not installed or not functional, the presence of functional alarms does not eliminate the risk of death. Functional smoke alarms were found in 34% of residential fire deaths between 2000 and 2004, and the mortality rate in residences with functional smoke alarms was 0.55 per 100 reported fires.[33] The number of households with smoke alarms that do not work now outnumber the households with no alarms by a substantial margin.[34] Any program to ensure adequate protection must include smoke alarm maintenance. In one fifth of all homes with smoke alarms, none were working.[34]

In reality, people do not always evacuate when fire alarms sound. Fire alarms are intended to meet four objectives: 1) warning occupants, 2) stimulating them to respond immediately, 3) initiating the evacuation process, and thus 4) providing enough time to escape. In truth, however, rather than assuming that a fire is occurring, people who hear a fire alarm tend to seek the reason for the alarm, such as the smell of smoke. Once they do recognize a fire, instead of calling the fire department and evacuating, they may engage in other activities such as fighting the fire or collecting belongings. People often fail to respond for a variety of reasons: 1) sometimes the signal is not recognized as a fire alarm, being misinterpreted as a burglar, elevator, or security door alarm; 2) sometimes people do not know what they should do, particularly if they are outside the home environment such as in a commercial space; 3) because of nuisance alarms, people may not believe the smoke alarm signals a real danger; and 4) because of distance from the alarm, background noise, or individual characteristics, people may not hear the signal.[36]

Studies of unwanted alarms have consistently shown that smoke alarms produce far more nuisance activations than do real alarms. A study of Veterans Administration hospitals found 1 unwanted activation for every six devices per year and 15.8 unwanted activations for every real alarm.[37] The 2000 New Zealand smoke alarm installation follow-up study found that smoke alarms provided warnings of actual fires in 7% of the households, but 38% of the households reported problems with nuisance alarms.[38]

Regrettably, to some people, the stress of nuisance alarms outweighs the benefit of smoke alarm protection. A study in the United Kingdom during 1999 to 2002 conducted group and individual interviews with adults and children to explore their perceptions of fire risk, the benefits and problems associated with smoke alarms, and whether they would recommend smoke alarms to others. Some adults described feeling very stressed by false alarms and expressed resentment about the smoke alarm going off during what was perceived as normal cooking. The perception of some children was that smoke alarms activated any time someone was cooking. As a consequence, smoke alarm activations were not viewed as emergencies. The authors remarked, "In a population already managing a range of health risks, a public health intervention that makes mealtime more, rather than less, stressful, and where noise can threaten leisure or relationships with fellow occupants, alarms could pose a threat to immediate wellbeing."[39]

A Cochrane review of interventions to promote residential smoke alarms included controlled (randomized or nonrandomized) trials published between 1969 and 2007.[40] The effect of the interventions on the prevalence of owned and working smoke alarms and on the incidence of fires and burns was assessed. Of 26 completed trials, 17 were randomized. Counseling and educational interventions, with or without allocation of free or discounted smoke alarms, only modestly increased the likelihood of owning an alarm (odds ratio 1.36) and having an installed, functional alarm (odds ratio 1.29). Only one randomized controlled trial reported injury outcomes, and no effect was found on injuries, hospitalizations, or deaths from a smoke alarm donation program. Two trials showed that smoke alarm installation programs increase the likelihood of having a working smoke alarm, and one of these studies also noted a reduction in fire-related injuries. The reviewers concluded that 1) programs to promote smoke alarms have only a modest beneficial effect on ownership and function, 2) programs to promote smoke alarms have no demonstrated beneficial effects on fires or fire-related injuries, 3) community smoke alarm donation programs neither increase smoke alarm prevalence nor reduce fires and injuries, and 4) community smoke alarm installation programs increase the prevalence of functional alarms and decrease injuries.[40] There is a paucity of the type of data needed by practitioners and policymakers who are seeking to implement smoke alarm promotion interventions.[41]

Between 2003 and 2006 in the United States, smoke alarms were present but did not sound in 23% of home fire deaths.[34] When smoke alarms were not present on all floors of the residence, they sounded in only 4% of the fires and alerted occupants in only 2% of the fires. On the other hand, when interconnected smoke alarms are present on all floors, they sounded in half the fires and alerted occupants 26% of the time. Although hardwired alarms operated 91% of the time, battery-powered alarms sound in only 75% of fires. Of the alarms that failed to operate, 75% had missing, disconnected, or dead batteries.[34]

In a study in Dallas from 1991 to 1998, smoke alarms showed no protective efficacy in preventing burn injuries or fire deaths in fires started by arson or by children playing with matches or lighters, although alarms conferred protection against injuries and deaths from all other causes.[42] In rural North Carolina in 1988, the absence of a smoke alarm was relatively more lethal in the case of fires in which children were present and when no one in the house was impaired by alcohol or drug use. Moreover, the presence or absence of a smoke alarm had no correlation with the risk of death when a person with either a cognitive impairment or physical disability was present.[26]

In 1998, the Centers for Disease Control and Prevention (CDC), the U.S. Fire Administration, the Consumer Product Safety Commission, and several other national organizations combined efforts to develop the Smoke Alarm Installation and Fire Education (SAIFE) program. The plan includes recruiting local communities and community partners, hiring a local coordinator, canvassing neighborhood homes, installing long-lasting lithium-powered smoke alarms, and providing general fire safety education and 6-month follow-up to determine alarm functionality. In follow-up surveys, this program has demonstrated 90% functional alarms (of those the program installed), potentially saving 610 lives in the 16 states involved.[43]

Unfortunately, there are scarce data from low-income and middle-income countries (LMIC) on utilization of smoke alarms. In Mexico, only 9% of homes in the upper socioeconomic stratum had smoke alarms, and none of the homes in the poorest stratum had alarms. An injury prevention educational campaign that included promotion of smoke alarm installation and use had no effect on the use of smoke alarms. This was not surprising, however, considering that smoke alarms could not be purchased in any of the nearby retail stores.[44] Clearly, more work is needed in LMIC, starting with an analysis of the impact of residential fires on injury and mortality.

An Alaskan study compared photoelectric and ionization smoke alarms in rural Eskimo Inupiat villages and ionization smoke alarms where home area averaged roughly 1000 square feet or less. At the time of follow-up after installation, 81% of the ionization homes had working smoke alarms compared with 96% of the homes with photoelectric devices. Ninety-two percent of the ionization homes, but only 11% of the photoelectric homes, had experienced at least one false alarm. Ninety-three percent of the 69 ionization false alarms were due to cooking as were four of the six of the photoelectric false alarms. False alarms were more common in homes that were smaller, that used wood fuel for heat, and in which the smoke alarms were located near the cooking areas. Thus, photoelectric alarms may be the preferred choice for homes with limited living space, an observation that is relevant as smoke alarm installation programs are advanced in LMIC.[45]

PASSIVE PROTECTION FROM STRUCTURE FIRES

Recognizing the presence of smoke is not the same as being able to escape from the fire. There are many who cannot escape because of physical infirmity, alterations in level of consciousness, or young age. Prevention of burn injuries and fire deaths, as well as mitigation of fire damage, is effectively and efficiently accomplished through the combined use of smoke detectors and sprinkler systems.[46] Smoke detectors are triggered in the initial moments of the fire event; sprinklers act throughout the event to minimize spread of the fire and in some cases extinguish it. The National Fire Protection Association estimates that the fire death rate between 2003 and 2006 was 80% lower in structures protected by sprinklers. In homes with both smoke detectors and sprinklers, the chance of surviving a residential fire is nearly 97%.[46]

However, neither smoke detectors nor sprinklers or their combination will work effectively to protect certain individuals:

- Victims who act irrationally, who return to the fire after safely escaping, or who are unable to act to save themselves, such as people who are physically disabled, bedridden, or under restraint.
- Victims whose clothing is on fire and sustain fatal fire injuries from fires too small to activate smoke detectors or sprinklers.
- Victims who are unusually vulnerable to fire effects, such as older adults, and those impaired by alcohol or drugs.

Unfortunately, fewer than 2% of U.S. single-family dwellings are fitted with sprinkler systems.[47] San Clemente, CA, was the first U.S. jurisdiction to mandate installation of sprinklers in all new residential structures. The cost of installing sprinkler systems in new houses is approximately $1 to $2 per square foot; retrofitting sprinklers in an existing building is somewhat more expensive but is comparable to the cost of purchasing and installing new carpeting.

CONCLUSIONS AND RECOMMENDATIONS

The effectiveness and reliability of smoke alarms can be improved through advancements in technology, including 1) greater waking effectiveness for certain populations, 2) quicker, more certain responses to the range of fire types coupled with reduced nuisance alarms, and 3) more cost-effective ways to interconnect alarms in existing homes.[49] In addition, continued research is needed to improve the measurement and performance of smoke alarms. Improvements must be made in educational approaches that change behavior in regard to home escape planning, inspection and maintenance of smoke alarms, and the development of safe options for dealing with nuisance alarms. More research is needed regarding the nature of human behavior in residential fires, to determine effective warning cues, increase the perceived value of immediate escape, promote the use of escape skills under stress, and design strategies to counteract the learned irrelevance of alarms.[49]

The following list is based on recommendations for use of smoke alarms from the National Fire Protection Association[50]:

- Ensure that smoke alarms are working by testing monthly, replacing batteries at least yearly, and performing maintenance as instructed by the manufacturer. (Use of lithium batteries ensures that the alarm will function for several years. All alarms should be replaced every 8 to 10 years, because of dust and moisture accumulation, clouding of the receptor and lens of photoelectric devices, and degradation of Americium-421 in ionization alarms.)
- Smoke alarms should be installed on every level of the home, outside each sleeping area, and inside each bedroom.
- Smoke alarms should be interconnected so that a fire detected by any of them will trigger the other alarms to sound.
- Develop an escape plan so that all occupants know what to do when a smoke alarm sounds.
- Use both ionization and photoelectric alarms because their effectiveness varies with how much flame is present in the fire.
- Install smoke alarms at a safe distance from sources such as kitchen stoves to minimize the number of nuisance alarms. Under no circumstances should an alarm be disabled because of repeated nuisance alarms—it should be replaced or repositioned.

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