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Epidemiology of Traumatic Injuries from Earthquakes

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Abbreviation: MMI, Modified Mercalli Intensity.

INTRODUCTION

More than 500,000 earthquakes are documented each year. Although the vast majority are too small or too remotely located to be felt by humans, approximately 3,000 are perceptible by human populations, of which seven to 11 result in significant loss of life (1, 2). Over the last 30 years, a yearly average of 21 earthquakes were reported, disasters defined as events resulting in more than 10 deaths, more than 100 people affected, a request for international assistance, or a declaration of a state of emergency (3). This average has increased to more than 30 in the last 5 years. In addition to loss of life, earthquakes cause considerably more nonfatal traumatic injuries and long-term damage to transportation, communication, and financial infrastructures; yet, only recently has there been a recognized need to routinely collect data on these less severe effects.

In the past 25 years, over 530,000 deaths have been reported from earthquakes, with death tolls from major earthquakes ranging from fewer than five to more than 240,000 (1, 3). Table 1 shows characteristics of 32 selected earthquakes that occurred from 1985 to 2003. These earthquakes show substantial variability in the number of deaths and in magnitude. Epidemiologic methods for describing causal associations are a promising approach to account for this variability and to identify potential avenues for preparedness and mitigation.

Earthquakes are not randomly distributed but are concentrated in regions where tectonic plates that compose the earth's surface coincide (4–7). Populations located above plate activity are at greatest risk of earthquake-related morbidity and mortality, such as communities along the Pacific Rim (e.g., the western edge of North and South America), along island chains (e.g., Japan and the Aleutians), and boundaries between certain continents (e.g., along the Himalayas to central Asia to the Caucasus Mountains and to the Mediterranean Sea) (4, 7).

Populations continue to grow in many of these seismically active regions, particularly urban communities along the western United States and in Japan, China, South America, and India (6, 8, 9). By 2030, it is anticipated that 5 billion people, about 60 percent of the world's population, will occupy urban areas. The fastest rates of growth are projected in the less developed regions of the world (9). Earthquakes that strike urban centers have the potential to cause substantial damage and death given the greater concentration of people, modern construction materials and building techniques, and complex transportation, communication, commercial, and residential infrastructures (10). However, rural populations at risk face different challenges, such as isolation from responders and the potential for substandard houses and buildings. Hence, we face multiple challenges as public health professionals to prevent and reduce earthquake-related morbidity and mortality in this increasingly complex environment. To design programs to prepare for earthquakes and mitigate their effects, we must achieve a comprehensive understanding of the risks for earthquake-related injuries.

In this paper, we highlight findings from and methods utilized in various population-based epidemiologic studies identified through an extensive literature search of published

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TABLE 1. Date, magnitude, and number of persons killed in selected earthquakes occurring from 1985 to 2003

Earthquake location	Date	Magnitude	No. of persons killed	Data source (reference no.)
Michoacan, Mexico	September 19, 1985	8.0–8.1	9,500–10,000	USGS* (54), EM-DAT* (3)
San Salvador	October 10, 1986	5.1–5.6	1,500	Durkin (55)
Whittier Narrows, California	October 1, 1987	5.9	8	USGS (54)
Yunan, China	November 6, 1988	7.2–7.6	748–939	EERI* (1991, 25/9), EM-DAT (3)
Spitak, Armenia	December 7, 1988	6.9	25,000	EERI (1989, 23/5), Armenian et al. (15)
Loma Prieta, California	October 18, 1989	6.9–7.1	62–63	USGS (54), EERI (1989, 23/11)
Manjil, Iran	June 21, 1990	7.3–7.7	>35,000	EERI (1990, 24/12), EM-DAT (3)
Luzon, Philippines	July 16, 1990	7.7	1,283	EERI (1990, 24/10), Roces et al. (29)
Costa Rica	April 22, 1991	7.6	47–52	EERI (1991, 25/6, 9)
Sierra Madre, California	June 28, 1991	5.6–5.8	2	USGS (54), EERI (1991, 25/8), EERI (1992, 26/1)
Garhwal, India	October 20, 1991	7.1	768	EERI (1992, 26/2)
Erzincan, Turkey	March 13, 1992	7.4	>800	USGS (54), EERI special earthquake report (1993)
Landers and Big Bear, California	June 28, 1992	7.4 in Landers, 6.5 in Big Bear	1–3	USGS (54), EERI (1992, 26/9)
Nicaragua	September 1, 1992	7	179	USGS (54), EM-DAT (3)
Cairo, Egypt	October 12, 1992	5.5–5.9	490–552	EERI (1992, 26/11,12), EM-DAT (3)
Latur-Killari, India	September 29, 1993	6.2–6.4	9,748–10,000	USGS (54), EERI (1994, 28/1)
Northridge, California	January 17, 1994	6.7	33	Peek-Asa et al. (32)
Kobe, Japan (Hyogo-Ken Nanbu)	January 17, 1995	6.9–7.2	~5,000–5,502	USGS (54), EERI reconnaissance report, Kuwagata et al. (56)
Ardekul, Iran	May 10, 1997	7.1–7.3	1,568–1,728	EERI (1997, 31/9) , EM-DAT (3)
Jabalpur, India	May 22, 1997	5.8–6.0	38–43	USGS (54), EERI special earthquake report (1997), EM-DAT (3)
Cariaco, Venezuela	July 9, 1997	6.7–6.9	73–80	EERI special earthquake report (1997), EM-DAT (3)
Colombia	January 25, 1999	6.2	1,185	USGS (54)
Izmit, Turkey	August 17, 1999	7.4–7.8	17,118–17,439	USGS (54), Mitchell (57), EM-DAT (3)
Greece	September 7, 1999	5.9	140	EERI special earthquake report (1999)
Chi-chi, Taiwan	September 21, 1999	7.6–7.7	2,347–2,471	USGS (54), Goltz et al. (58), Chan et al. (14)
Duzce, Turkey	November 12, 1999	7.1–7.2	400–897	USGS (54)
El Salvador	January 13, 2001	7.4–7.7	844	USGS (54), EERI (2001, 35/7)
Gujarat, India	January 26, 2001	7.7	19,727–20,085	USGS (54), CIRES,* EM-DAT (3)
Coastal Peru	June 26, 2001	8.2–8.4	75–145	USGS (54), Shoaf et al. (59), EM-DAT (3)
Italy	October 31, 2002	5.4–5.7	30	EERI (2003, 37/1)
Colima, Mexico	January 21, 2003	7.6	29	EM-DAT (3)
Bam, Iran	December 26, 2003	6.6	26,796–31,000	USGS (54), EM-DAT (3)

* USGS, US Geological Survey (major offices in Reston, Virginia; Golden, Colorado; and Menlo Park, California); EM-DAT, Emergency Disasters Data Base; EERI, Earthquake Engineering Research Institute (Oakland, California; except where otherwise noted, the information in parentheses refers to newsletters from the Institute: year published, volume/issue no.); CIRES, Cooperative Institute for Research in Environmental Sciences (Boulder, Colorado).

studies on earthquake-related traumatic injuries in MEDLINE and PubMed, as well as conference proceedings. We focused our search on studies of acute traumatic injuries, excluding studies of long-term health outcomes such as crush syndrome and psychological sequelae and those that did not include direct measurements of human health outcomes, such as statistical casualty modeling predictions. Supplemental information was also collected from technical reports and databases maintained by government agencies and research institutions identified from online searches.

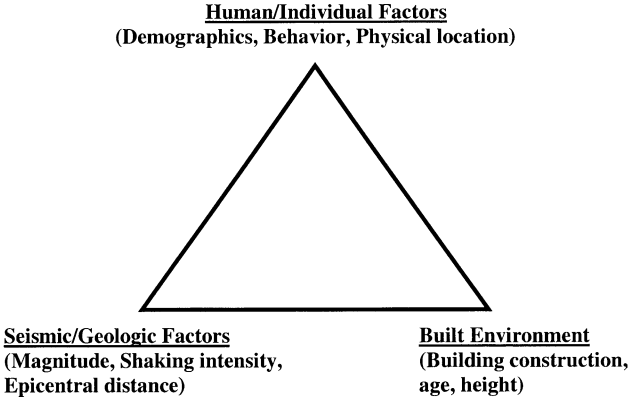

FIGURE 1. Epidemiologic triangle.

EARTHQUAKES AND THE CLASSIC EPIDEMIOLOGIC MODEL

The classic epidemiologic model of agent, host, and environment can be applied to earthquake-related traumatic injuries (figure 1) (11, 12). Three apexes of the triangle are defined as follows: 1) the host as the individual, 2) the agent as the energy transferred from the quake, and 3) the environment as the buildings and infrastructures where humans are situated. The challenge for researchers is to characterize the individual, the earthquake-energy-producing qualities, and the built environment to understand the causal pathway to injury.

Host characteristics

Host factors encompass the demographics, behavioral response, and physical resiliency of individuals (13). The literature shows inconsistent associations between injury and demographics. For example, females had an elevated risk of traumatic injury during the 1994 Northridge, California; 1999 Taiwan; and 1988 Armenian earthquakes (13–15). Death rates increased with age for these same earthquakes and for the 1995 Hanshin-Awaji, Japan, earthquake (13–17). Death rates were similar by gender for the 1980 southern Italy and the 1999 Chi-Chi, Taiwan, earthquakes (14, 18), and they were similar by age group for the 1980 Italian earthquake (13, 18). In contrast, in a report of the 1976 Guatemalan earthquake, which included deaths of children, death rates showed a bimodal pattern, with peaks among the youngest and oldest age groups (19). People with physical disabilities have also been identified as having an increased risk (20).

Behavior is another type of human factor. Despite strong and swift ground motion, a great deal of activity occurs that affects survival during earthquakes. Victims of the 1982 off-Urakawa earthquake reported staying still, moving in directed or undirected ways, turning off oil stoves to prevent fires, protecting property from falling, and running outside (21). Running out of buildings was related to decreased casualty rates during earthquakes in southern Italy and Armenia (19, 22). During the 1988 Armenian earthquake, death and injury was substantially elevated among those who remained indoors compared with those who exited buildings (22). In contrast, moving rather than staying still during the 1994 Northridge earthquake doubled the odds of injury (23).

Agent characteristics

Magnitude and intensity are measures of an earthquake's strength. The initial focus of ground motion, the hypocenter, is often located below the earth's surface, while the epicenter is the point on the surface vertically above the hypocenter (24). Magnitude, usually measured by using the Richter scale, is the total energy from seismic or elastic waves radiated from approximately the epicenter of a single earthquake and is estimated from instrument observations (6, 24). For studies of a single earthquake, magnitude has limited value, providing one exposure measure for the entire earthquake but not for individuals.

With information about individual locations during the earthquake, epicentral latitude and longitude can be used to estimate individual distance from the epicenter. Although increasing distance from the epicenter during the 1994 Northridge earthquake showed an inverse relation with risk of injury, distance was a poor predictor of death and injury (13, 25). Distance from the epicenter may misrepresent localized strength of shaking because other factors influence wave transmission during a seismic event, including ground composition, liquefaction, and landslide susceptibility (24, 26). For example, an area with alluvial soil, which has a high water content and thus is very effective in transmitting energy waves, may exhibit high mortality, morbidity, and damage even if far removed from the epicenter (7). Two studies found positive, but imprecise associations between rock surfaces and injury during the 1994 Northridge quake (13, 16).

Intensity, in contrast to magnitude, is the earthquake effect at specific locations (6). Two standard measures are peak ground acceleration and Modified Mercalli Intensity (MMI).

Peak ground acceleration quantifies seismic energy based on the speed of acceleration of the ground at localized points. Acceleration for specific latitude and longitude coordinates is interpolated from underground sensors. Because these sensors are in place in only highly developed, earthquake-prone areas such as Japan and California, the use of peak ground acceleration as a worldwide measure is limited. If available, it can be a useful objective exposure measurement providing precise estimates of acceleration at specific locations not influenced by the built environment or the perception of motion. In studies of California earthquakes, peak ground acceleration was highly predictive of both fatal and nonfatal injury (13, 16, 23, 25).

MMI is a subjective scale of earthquake intensity based on a 12-point scale (table 2) (6). Following an earthquake, US Postal Service employees are interviewed about their perceived shaking experience in the areas near their offices using one of the 12 categories (23). Shaking intensity is then interpolated so that MMI for a defined area, such as a census tract or zip code, can be assigned.

TABLE 2. Categories of the Modified Mercalli Intensity scale to measure earthquake intensity*

Intensity category	Abbreviated description of effects
I	Not felt except by a very few under especially favorable conditions.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage is total; large waves propagate along ground surface, and it is nearly impossible to stand; objects thrown up into the air.

* Abridged from Noji (6).

As a perceived measure, MMI is subject to individual variation, and its validity depends on the sample interviewed. Little information can be found in the literature about how respondents are sampled and queried. In addition, MMI does not distinguish between effects due to ground motion, soil, and other geophysical measures or to characteristics of the built environment (e.g., a building, bridge, or road). MMI is thus highly correlated with building damage. Because MMI describes shaking as perceived by humans, it has been the geophysical measure most closely related to death and traumatic injury (13, 16, 23, 27).

Other earthquake factors can affect mortality, including the time of day (23). For example, both the 1994 Northridge and 1995 Kobe earthquakes occurred at night. Had they occurred during the day, people could have been exposed to different environmental hazards in the workplace, at schools, in public locations, or on roadways or thoroughfares. This scenario would likely have increased the death rate because many more individuals would have been using vulnerable transportation systems and been located in large, multiple-story buildings. In both southern California and Japan, the majority of single-family homes are wooden structures that are relatively stable in earthquakes. However, analyses of the timing of earthquakes and potential exposures can be conducted only in the context of multiearthquake studies.

Mortality and morbidity can also be influenced by secondary geologic events, most frequently landslides and tsunamis (shaking-generated tidal waves). Discussion of these events is beyond the scope of this article.

Environmental characteristics

The built environment. Building construction and the propensity for buildings to collapse have significantly contributed to mortality during earthquakes in Guatemala, Armenia, the Philippines, Turkey, and Japan (8, 18, 28, 29). In Guatemala, all deaths and serious injuries occurred during the collapse of heavy adobe brick structures, which composed 85 percent of the homes, during the earthquake. These buildings had weak walls but heavy ceilings; during the earthquake, the walls gave way and the heavy ceilings crushed or entrapped occupants. However, the age and size of these structures had no observed effect (18). In Armenia, risk of death was greater for persons located on the upper floors of concrete panel buildings and those in precast-concrete frame buildings (15, 28). In the Philippines, individuals in concrete structures had a higher odds of death than those in wood buildings (29). During the 1992 Turkey earthquake, 92 percent of the deaths occurring in buildings were in newly constructed midrise, unreinforced, masonry structures (8). During these earthquakes, rigid concrete structures and masonry buildings could not attenuate ground motion and were thus prone to collapse.

However, during the 1994 Northridge earthquake, there appeared to be no relation between severe injury and building composition. More than 96 percent of structures were wood-frame buildings, which are resilient to collapse. The building stock in southern California has been subject to building codes and retrofitting that make buildings less vulnerable to collapse. Instead, associations were reported between severe injury and the age and main use of the building. Risk was moderately greater in newer buildings—those constructed after 1975 (13, 16)—and in residential multiple-unit and commercial structures (13) when compared with single-family homes.

Transportation infrastructures. Engineering studies have identified structures such as bridges and roadways as highly vulnerable to earthquake damage, and deaths on bridges have been reported in many earthquakes (30–32). Collapse of freeway structures was involved in 81 percent of deaths on public roadways in Loma Prieta, California (31). Motor vehicle crash fatalities and injuries were tied to damage to transportation infrastructures, such as nonfunctional traffic signals and road lighting (13, 31, 32). During the Northridge incident, 15 percent of fatal injuries were motor vehicle related and were primarily due to disruptions in traffic control devices (32).

Interactions between the host, agent, and environment. Although seismic, environmental, and individual characteristics have independent associations with death and injury, these factors also interact in many situations to increase risk. The effect of individual (host) characteristics on injury during earthquakes greatly depends on the type of building. For example, in the Great Hanshin-Awaji earthquake, the risk of injury in intact or partially destroyed dwellings was more than five times higher for individuals with a physical disability than for those without one (20). In turn, the vulnerability of any single building will depend on its seismic stability but will also be strongly affected by the seismic characteristics of the earthquake and the geophysical properties of the ground on which the building stands. For example, seismically stable structures located on vulnerable soil types may collapse in an earthquake, while less stable structures located on solid rock may remain standing.

The interaction of individual characteristics and human behavior with the built environment has been the subject of little research but is a promising avenue for epidemiologic study. For example, persons entrapped by debris from a damaged structure are more likely to die than those not entrapped (19, 28). Yet, to our knowledge, risk of entrapment has not been specifically examined across multiple building types or earthquakes, nor have behaviors that increase risk of entrapment been studied. Entrapment has been shown to be particularly frequent during high-intensity earthquakes and in concrete structures, as observed during the 1988 Armenian and 1980 south Italy earthquakes (19, 28). However, few cases of entrapment were reported from modern California earthquakes, which was likely due to the predominance of wood structures less vulnerable to collapse (16, 32). In California, injuries occurred when people moved during and just after the earthquake, such as to escape the building (16, 32). These injuries were the result of falling, being hit by fallen objects, and stepping on broken glass. Decisions on whether to exit a building may depend on the likelihood of the building to collapse, which in turn will depend on characteristics of the building, the land on which the building sits, and the seismology and geology of the earthquake.

A complete understanding of the independent and interdependent risk factors across individual, built environment, and seismic characteristics requires studies of multiple earthquakes. Data must then be collected simultaneously on all of these three categories. Thus far, most earthquake studies have focused on one or two of these characteristics, and few have incorporated analyses that encompass all potential risks.

EARTHQUAKE RESEARCH METHODS

Capturing the population at risk

Two key features of epidemiologic studies are the identification of an at-risk population and the enumeration of this population. Enumeration, either during or prior to an earthquake, is one of the greatest challenges faced by disaster researchers.

Existing census data are commonly used to describe the at-risk resident population prior to an earthquake but are associated with special problems for disaster studies. Overall, census data assume that the population throughout the area is at equal risk, while actual ground shaking will vary considerably over population areas. This problem can be overcome by using census-tract-specific estimates tied to localized measures of intensity, but such census data are often outdated in developed countries and not available in undeveloped countries. In addition, census data cannot be used to identify specific locations of individuals when the event occurs. Census-based population measures will thus be highly influenced by such factors as whether major damage occurred primarily in residential compared with commercial areas, population movement in relation to the time of the earthquake (e.g., during the workday or at night), or whether the area has a high volume of tourists.

Surveys of subpopulations have been used to obtain rate denominators that describe a specific population at risk. For example, Armenian et al. (15) surveyed a cohort of workers and their families who were affected by the 1988 Armenian earthquake. Using this method, these authors were able to measure the specific location of each cohort member to assess risk of death and injury by the type of and floor location within buildings. Other studies have used phone and in-person interviews of populations following the earthquake (23, 33). In post-impact surveys, identification of a representative population at risk is severely limited by selective survival and population movement (6). Earthquakes disrupt patterns of daily life in a community (29), whereby individuals and their entire households may be displaced, relocated, or killed. These individuals, who represent the highest-risk component of the population, will be the most difficult to identify.

Case definition and ascertainment

Information on earthquake-related traumatic death and injury can be obtained from multiple data sources; each has limitations that must be weighted with the specific study hypothesis. First estimates of casualties usually come from phone-based surveys of health-care providers and are used to calculate the numbers of people being treated. Such surveys have no protocol for differentiating injuries that are and are not earthquake related, and the validity of these estimates has not been established. Secondary data sources include death certificates, medical examiner records, and medical records. Standard coding mechanisms used for these records do not allow direct ascertainment of the role of the earthquake, and individual record review is usually necessary. An additional limitation is the difficulty in accessing records for nonsevere injuries in persons not admitted to the hospital. Surveys can be used as a primary source of information on injuries, particularly less severe injuries.

Although surveys can provide detailed descriptions of injury causes, they are limited because of the difficulty in identifying the injured and proxies for those killed. Definitions of earthquake-related death and injury vary widely throughout the literature (27). Some studies include all deaths or injuries, regardless of cause, and will overestimate the effects of the earthquake. Other studies include broad definitions of health events, including cardiac arrest, suicides, and preterm pregnancy. Because of differing sources of information and case definitions, reports on the number of deaths vary widely for the same event (26, 33).

Study designs

Four types of epidemiologic designs have been used to study health outcomes from earthquakes: case-series, cross-sectional, case-control, and cohort studies. Case-series studies are most common in the literature and usually include a single hospital sample not representative of the spectrum of injuries sustained in the earthquake. Without information on the population at risk, measures of frequency and association cannot be estimated. However, case-series studies have been useful to identify the clinical features and specialized treatment of specific types of earthquake-related injuries such as crush syndrome (34, 35).

Cross-sectional studies are also common and typically use a post-earthquake survey to assess various exposures and outcomes. These surveys are an efficient way to collect information about behaviors during and after disasters; precise location during the event; and a variety of outcomes experienced during the earthquake, including less-severe injuries treated outside the hospital setting (8, 14, 18, 19, 23, 33). Because death is a common outcome of interest, some studies have used proxy interviews for deceased subjects (18). Limitations of cross-sectional studies of earthquakes include poor sampling methods leading to nonrepresentative samples and bias from selective survival, population movement, and recall.

Case-control studies are an efficient design to use to estimate specific risks, and their use for studying earthquake-related outcomes has increased during the last decade. Cases can be collected from multiple sources of data, including existing records or surveys. Controls should be sampled from the same population from which the cases arose (e.g., controls from the community). Finding a representative control group is the most complicated feature of the case-control design because of the difficulty in defining a base population for an earthquake. Matching can be used to control for confounding that might be difficult to measure on a population level, such as location within a building. For example, controls have been matched to cases by geographic location and demographic characteristics (13, 20, 22). Overmatching, in which cases and controls are too closely matched, is problematic in earthquake studies with no identified base population. For example, Roces et al. (29) matched injured cases to uninjured family members to estimate the risk of mortality associated with such factors as building type and being inside a building compared with being outside a building. However, family members are likely to be in the same structures and to be located together.

Variations on case-control studies are also prominent in the literature. Tanaka et al. (17) compared earthquake-related hospital admissions with ‘‘controls’’ admitted to the same hospitals for non-earthquake-related trauma and illness. Armenian et al. (22) defined cases as those with more severe injuries treated at clinics and controls as those with minor injuries not requiring hospitalization.

The ideal epidemiologic design is the cohort study. In earthquake studies, follow-up could be substantially short if only direct consequences are examined, or it could be lengthier to account for injuries after extrication or during post-earthquake activities. Armenian et al. (15) were the first authors to conduct an earthquake cohort study by using data from the 1988 Armenian earthquake. The cohort consisted of employees of the Ministry of Health living in the earthquake region 1 day prior to impact. Some loss to follow-up of the cohort occurred because of death, relocation, and missing contact information. Cohort studies are not commonly conducted to study earthquake-related injuries because of the difficulties in identifying a defined cohort. Part of the problem is that we cannot define when and where earthquakes will occur and therefore must necessarily rely on retrospective cohorts (15).

Ecologic studies have rarely been used to assess earthquakes. For 16 earthquakes, Alexander (1) summarized the numbers of dead and injured, the magnitude, and building damage. He found no associations of the ratio of total casualties with the total number of damaged buildings across these earthquakes. However, estimates did not include denominator data and therefore did not account for differences in the population at risk or the types of buildings. Most existing studies examine specific risk patterns and outcomes for a single earthquake, and factors specific to one earthquake cannot easily be generalized to all earthquakes. Ecologic studies that combine characteristics of several earthquakes have the potential to examine variability in population health outcomes across different earthquake characteristics.

Analytic approaches

The earthquake engineering field uses sophisticated methods to estimate casualties. These Casualty Estimation Models calculate a probable number of dead and/or injured by modeling the number of collapsed structures expected within an inventory of buildings, an expected average number of persons per structure, expected death rates, and injury ratios (8). The models are developed by using simulated data but do not include individual-level factors such as age, gender, and location of occupants within buildings (13).

In contrast, epidemiologic modeling incorporates real population data with building and seismic data. Figure 1 provides a simple theoretical framework for use in multivariate causal modeling. Statistical analyses need to simultaneously consider all three apexes of the triangle, that is, the risk categories of human/individual, seismic/geologic, and building/structural. Recent studies have begun to incorporate these issues (13). To counter sparse data in modeling, methods such as restricting the population by a potential confounder can be used. By restricting their study populations to communities in MMI regions of intensity VIII or higher, Noji et al. (28) and de Bruycker et al. (18, 36) essentially controlled for confounding by earthquake shaking intensity. In both of these studies, there was no need to collect or adjust for shaking-intensity variables. However, findings were limited to those from communities of high shaking intensity.

PREVENTION MEASURES

Disaster preparedness, mitigation, response, and recovery

Public health professionals can help communities prepare for disasters and protect the health of the affected population through prevention and protection programs (37). The cycle of crisis planning provides a systematic approach for preparing for and managing disasters (figure 2) (38). This model includes four cyclical stages of mitigation, preparedness, response, and recovery. Mitigation refers to activities that reduce suffering and hasten recovery (39). Preparedness helps communities react to an emergency through planning, exercises, and training. Response actions (e.g., warnings, evacuation, sheltering; fire-related, legal, medical actions) taken before, during, and after a disaster may save lives and minimize property damage. Recovery refers to rebuilding the lives of the affected population and includes reconstructing infrastructures and facilities (for more information, refer to the following website: www.fema.gov).

Findings from epidemiologic studies should inform the development of specific components of the cycle of crisis planning (38). For example, pre-earthquake structural mitigation was recommended in response to deaths caused when seismically unstable structures collapsed (15, 18, 29). During the pre-earthquake phase, development and enforcement of building safety codes can reduce the probability of building-collapse-related injury (29). In addition, earthquake mitigation should be considered in land-use and building design practices for community development (39). Communities could elect to build structures in less-earthquake-prone areas identified after hazard assessments (39, 40), and heavy construction materials such as concrete may be excluded in earthquake-prone areas (15). Such was the case in Costa Rica, whose 1910 law forbids construction of adobe buildings and likely prevented deaths and injury after the 1991 earthquake (41). Unfortunately, many other varieties of building designs have not been "tested" in earthquakes. Hence, policies for earthquake-resistant building construction are incomplete and inadequate (8), which is probably one reason why, as of 1999, more than half of 30,000 communities in the United States had not adopted a building code (39). Even those communities with building codes lack inspection programs for enforcement (39). Thus, comprehensive research, evaluation, and enforcement of building policies are needed to adequately address seismic vulnerability and reduce earthquake injury risks.

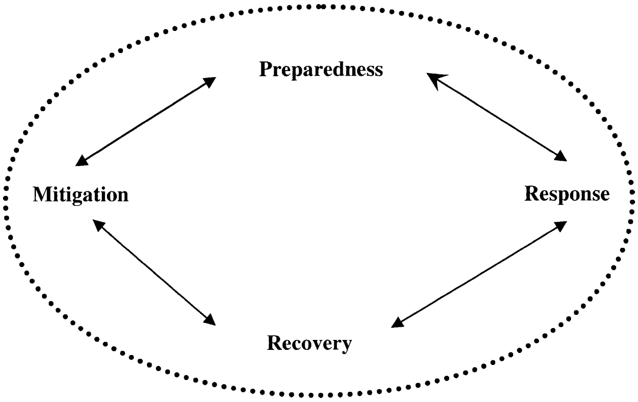

FIGURE 2. Cycle of crisis planning (38).

Researchers have also suggested response activities based on epidemiologic risk patterns. During the post-impact phase, improved search and rescue methods and effective medical care may reduce injuries among those trapped in collapsed buildings (15, 22). However, insufficient and uncoordinated medical responses were reported during the Armenian and Costa Rica earthquakes (41, 42). Communication must be improved to organize local and external responders who either operate independently or inundate the affected region with useless or redundant resources (6, 41).

Behavioral approaches can also be improved through research. After the Armenian earthquake, investigators suggested that communities with heavy concrete buildings prone to collapse adopt behavioral modification methods to teach people to escape outside when an earthquake occurs (15). Because many injuries during the Northridge quake were attributed to objects/contents in the household, Mahue-Giangreco et al. (16) challenges traditional "duck, cover, and hold" strategies and recommends other types of positioning and holding methods to protect against fallen objects.

Training is another important element of preparedness. To reduce deaths during earthquakes, immediate prehospital care should be provided for life-threatening injuries within the first 6 hours (43). During large events, rescue teams cannot reach all affected individuals in this time frame. The local community should be trained to participate in rescue activities and post-rescue treatment (15, 36, 39, 41).

The period of recovery following a disaster should include mitigation policies for long-term reduction of risk (44–46). Improving the seismic stability of buildings, and policies that require such changes, can occur during housing reconstruction (47). The recovery period can be the most opportune time to implement other prevention methods such as training and behavioral modification. Such activities will be most effective if based on sound scientific knowledge.

CONCLUSION

Earthquakes will continue to affect human populations. With technologic advances, increasingly complex infrastructures, and new building designs, the built environment will evolve over time. Shifts in population locations and characteristics will accompany these environmental changes. Every earthquake is different, as is every population affected. Thus, there is a critical need for evidence-based prevention and preparedness efforts, and earthquakes provide an ongoing challenge to the field of epidemiology.

Overcoming these challenges will require increased efforts to establish better methods of collecting and sharing data across agencies at the local, national, and international levels. Continued collaborative research efforts among epidemiologists, engineers, seismologists, and geographers will enable creation of databases that contain information about multiple earthquakes. Data sharing can also lead to more comparable definitions and methodological approaches, more precise measures of exposure and risk, and access to information about populations to serve as rate denominators. For example, efforts to catalogue populations by using Geographical Information Systems can provide immediate information that can be used by first responders to pinpoint locations, buildings, and infrastructures during response, and they can also be used by researchers to build exposure databases. Linking Geographical Information Systems data with other databases, such as information collected through the census, can provide additional details about population and building characteristics.

Improved research methodologies and greater access to information can in turn be used by disaster managers to organize mitigation and response efforts (487). Protocols for both immediate and long-term response can be developed and tested in different types of populations and environments. Doing so requires that anecdotal evidence, lessons learned, and recommendations for response and relief activities commonly reported for single earthquakes be compiled, compared, and evaluated (42, 49–53). These accumulated data can provide a catalogue of the various methods for delivering medical services, surveillance, evacuating and transporting the dead and injured, and search and rescue activity. Ultimately, this information can be used for specialized teams in earthquake-prone areas that can develop response protocols specific to the risk profile of the population, the built environment, and earthquake characteristics.

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