Lightning Injuries

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HISTORICAL OVERVIEW

Lightning has caused injuries to humans since man evolved on Earth. Lightning played a major part in nearly every ancient religion and culture and continues to engender stories, perceptions, and myths in modern cultures. Older 1,17

Priests, the earliest astronomers and meteorologists, became proficient at weather prediction, interpreting changes in weather as omens of good or bad fortune, sometimes to the advantage of their political mentors. Greek artists incorporated lightning symbols representing Zeus’s tool of warning or favor. Romans killed by lightning were considered disfavored and were denied burial rituals. Many Roman emperors wore laurel wreaths or sealskin to ward off lightning strikes. Thursday is named for Thor, the Norse god of thunder. Chinese mythology had a goddess of lightning in the “Ministry of Thunderstorms.” Lightning played a role in Buddhist symbolism.

Although lightning is most frequently rendered as fire, it also has been represented in French and Asian histories as stone axes hurled from the heavens. Africans and some Native American tribes picture lightning as a Thunderbird. The Navajos credit the creation of the Grand Canyon to lightning.20 Native Australian stories incorporate lightning symbols, where the lightning spirit is depicted as having axes attached to his joints, beating together to make thunder.

People in both developed and third world countries often regard lightning and thunder with a great deal of fear as mysterious, uncontrollable, and unmanageable. In the 1990s and early 2000s, there was a series of lightning injuries at soccer games in Africa. In one incident, where only members of one team were injured, it was ascribed to witchcraft on the part of the other team. Even in “civilized” Western societies, lightning can take on mystical significance. When lightning struck an English cathedral just before enthronement of a controversial bishop in the late 20th century, some regarded it as an omen.

MYTHS, SUPERSTITIONS, AND MISCONCEPTIONS

The Roman author Pliny noted that a man who heard thunder was safe from the lightning stroke. This implies that the person who hears the thunder is far enough away from the lightning strike to survive it, although we now know they may still become injured. Persons so close that they cannot hear the thunder are much more likely to be injured. Persons who receive ground current are more likely to report both seeing the flash and hearing the stroke, indicating that the main stroke was some distance away.

Many myths about lightning, including the notion that lightning strikes are invariably fatal, persist (Box 3-1). According to an American study of cases reported in the lightning literature since 1900, lightning strike carries a mortality rate of 30% and morbidity rate of 70%.22 A slightly different statistical interpretation of the same data yielded a mortality figure of 20%.23 Because literature reports are usually biased toward the severe or interesting cases, case reviews tend to overestimate mortality rate. In reality, mortality rate may be as low as 5% to 10%.44

Most people suspect that the major cause of death is from burns. However, the only cause of immediate death is from cardiac arrest.42 Persons who are stunned or lose consciousness without cardiopulmonary arrest are highly unlikely to die, although they may still have serious, especially long-term, sequelae.44 Delayed causes of death include suicide induced by the life changes from disability wrought by lightning.49

Most people know to seek shelter when storm clouds roll overhead. Few realize that one of the most dangerous times for a fatal strike is before the storm.55 Lightning may travel nearly horizontally as far as 10 miles or more from the thunderstorm and seem to occur “out of a clear blue sky,” or at least by the day is still sunny when the person is located. The faster the storm is traveling and the more violent it is, the more likely a fatal strike will occur. Another time underestimated for the potential danger of lightning is the end of a thunderstorm, which has been shown to be as dangerous as the start of the storm.

The “30-30 rule” is now recommended for lightning safety.46 If you see lightning and count fewer than 30 seconds before you hear the thunder, you are already in danger and should be seeking shelter. Activities should not be resumed for at least 30 minutes after the last lightning is seen and the last thunder heard.56,191 To calculate your distance from lightning, take the number of seconds between the “flash” and the “bang” (flash-to-bang method) and divide by 5 to find the number of miles.198

The problem with the flash-to-bang method is that it is sometimes difficult to match the correct thunder to the correct lightning flash in an active storm. In addition, many people forget to divide by 5 and so overestimate the miles (and their safety factor) by a factor of five. Therefore, it is best to count to 30 seconds as a reasonable precaution and not worry about the distance involved or, better yet, seek shelter at the first sound
Box 3-1. The Most Common Myths and Facts

**NO TRUTH**

Lightning injuries are always fatal.
The cause of death from lightning injury is burns.
Burns are a major component of lightning injury.
Nothing is left of a person after a lightning strike except a pile of ashes.
Lightning victims have “entry” and “exit” points.
Lightning victims have internal burns.
One can predict the degree of lightning injury from the voltage, amperage, and polarity of the strike.
Metal (on the body or not) attracts lightning.
Lightning does not hit outside the rainstorm.
It is safe to wait until the rain arrives to evacuate.
It is safe to finish the game if lightning is nearby.
After the rainstorm passes and rain stops falling, it is safe to resume activity.
If you can see blue sky, lightning danger is minimal.
Lightning injuries cannot occur inside a building.
Rubber tires (shoes, raincoats, sitting on a backpack) protect a person from lightning.
Cellular phones attract lightning.
Golf, picnic, and other electrically grounded shelters are safe.
Grounding a building makes it safe from lightning damage.
Lightning victims remain electrified and dangerous to touch.
Lightning victims are easier to resuscitate than are other cardiac arrest victims.
If there are no outward signs of lightning injury, the damage cannot be serious.
Lightning victims usually require treatment similar to that for high-voltage electrical injuries with aggressive fluid resuscitation, urine alkalization, and fasciotomies.
Lightning survivors have few permanent problems.
Lightning never strikes the same place twice.
It is safe to seek shelter and dryness under a tree.
Tall objects provide a 45-degree cone of protection.
The majority of persons injured are golfers.

**SOME TRUTH**

Lightning always hits the highest object.
The “pointier” an object, the more likely it will be hit.

of thunder, especially if you are responsible for the safety of a group. Thunder is seldom audible more than 10 miles away and often much less audible in a city, on a mountainside opposite the thunderstorm, or in a noisy sports stadium.

The distance between successive lightning flashes may be as little as a few yards or as much as 5 miles plus or minus another 5 miles (a count of 50 seconds) depending on the terrain and other local geographic factors. One way to teach children lightning safety is to teach them: “If you see it, flee it; if you hear it, clear it.” Even better is “If thunder roars, go indoors.”

Most people believe they are immune from lightning strikes when inside a building. However, a number of injuries occur to persons who are in their homes or places of employment. Side flashes strike people through plumbing fixtures, telephones, and other appliances attached to the outside of the house by metal conductors. Earth potential rise (EPR) can be significant, and in one study was thought to account for 80% of telephone-related injuries. Cellular or portable phones offer complete protection from the electrical effects, although victims may suffer some damage from static in the earpiece similar to having a firecracker go off next to the ear. With a hard-wired phone, persons may suffer neurocognitive deficits, death, or a myriad of other lightning-related problems because the phone system in most houses is not grounded to the house’s electrical system and so acts as a conduit for lightning either to come into the home or to exit from it. Telephone companies include warnings in their directories about using telephones during thunderstorms.

Taking shelter in small sheds, such as hikers’ lean-tos or those on golf courses, can be especially dangerous when lightning splashes onto the inhabitants. Tent poles offer similar danger. Unfortunately, the most recently published National Fire Pro-
The Association (NFPA) Journal discusses protection that may be effective for the structural safety of the shelter but not adequate to protect people sheltered within from side flashes. Being in an inadequately protected open shelter may actually increase the lightning risk to any inhabitants who seek shelter in them by increasing the inhabitants' effective height.

The “crispy critter” myth is the belief that the victim struck by lightning bursts into flames or is reduced to a pile of ashes. In reality, lightning often flashes over the outside of a victim, sometimes blowing off the clothes but leaving few external signs of injury and few, if any, burns.

Two other myths held by the public and many physicians are that “If you’re not killed by lightning, you’ll be OK” and “If there are no outward signs of lightning injury, the damage can’t be serious.” Medical literature, because of lack of follow-up case reports, also implies that there are few permanent sequelae of lightning injury. Several permanent sequelae may occur. In addition, many lightning victims with significant sequelae have no evidence acutely of burns. Peripheral neuropathy, chronic pain syndromes, and neuropsychological symptoms, including severe short-term memory difficulty, difficulty processing new information, attention deficit, depression, and post-traumatic stress disorder, may be debilitating. It is regrettable that victims still feel that these very serious complications are not believed, especially by medical practitioners.

A myth still prevalent is that the lightning victim retains the charge and is dangerous to touch, because he or she is still “electric.” This myth has led to unnecessary deaths by delayed resuscitation efforts.

Medical literature and practice are plagued by myths that grew out of misread, misquoted, or misinterpreted data and continue to be propagated without further investigation. Not the least of these is the tenet that lightning victims who have resuscitation for several hours may still successfully recover. This belief seems to be grounded in the old idea of suspended animation—the concept that lightning is capable of shutting off systemic and cerebral metabolism, allowing rescuers a longer period in which to resuscitate the patient. This concept, credited to Tausch,

In a study of lightning survivors, Andrews, Colquhoun, and Darveniza have shown increasing prolongation of the QT interval, bringing up the theoretic possibility of torsades de pointes as a mechanism for the suspended animation reports. There is new evidence from animal experiments to support the teaching that respiratory arrest may persist longer than cardiac arrest.

One study, in which Australian sheep were hit with simulated lightning strokes, showed histologic evidence of damage to the respiratory centers located beneath the fourth ventricle. Prolonged assisted ventilation may in some cases be successful after cardiac activity has returned.

Another series of animal experiments has shown that it is possible to obtain the skin changes (keratographic markings), primary and secondary arrest with prolonged respiratory arrest, and temporary lower extremity paralysis with simulated lightning strike.

Several booklets listing precautions for personal lightning protection appeared in the late 1700s and early 1800s. One of the superstitions listed was that humans, by their presence, could attract lightning to a nearby object. A book of the times, *Catechism of Thunderstorms*, illustrated other myths. Lightning was said to follow the draft of warm air behind a horse-drawn cart, so that coachmen were cautioned to walk their horses slowly through a storm.

Historically, many remedies for resuscitation of lightning victims have been offered. On July 15, 1889, Alfred West testified in a New York court that he was revived by “drawing out the electricity” when his feet were placed in warm water while his rescuer pulled on Mr. West’s toes with one hand and milked a cow with the other.

Other early attempts at resuscitation included friction to the bare skin, dousing the victim with a bucket of cold water, and chest compression. An early attempt at cardiopulmonary resuscitation was given in 1807 when mouth-to-mouth ventilation was used for lightning victims, and it was proposed that gentle electric shocks from galvanic batteries passed through the chest might be successful in resuscitating a victim of lightning. Before that, Benjamin Franklin had purposely electrocuted a chicken during a lightning experiment and reported successful, albeit temporary, resuscitation with mouth-to-beak ventilation.

A myth in current treatment is that lightning injuries should be treated like other high-voltage electrical injuries. Although lightning as an electric phenomenon follows the same laws of physics, the injuries seen with lightning are very different from high-voltage injuries and should be treated differently if iatrogenic morbidity and mortality are to be avoided.

“Lightning never strikes the same place twice.” In reality, the Empire State Building and the Sears Tower are hit dozens of times a year, as are mountaintops and radio-television towers. If the circumstances facilitating the original lightning strike are still in effect in an area, the laws of nature will encourage further lightning strikes.

**Other Myths**

1. Victims may have “internal burns.” False. There may be cellular damage and certainly nervous system damage but rarely, if ever, internal burns such as those suffered with high-voltage electrical injuries. However, some physicians use this euphemism with patients to explain their pain and neurologic injuries.

2. Wearing rubber-soled shoes, raincoats, sitting on a foam pad or backpack, or the like will protect a person. False. If lightning has burned its way a mile or more through the air, which is an excellent insulator, it is foolish to believe that a fraction of an inch of rubber or that a few inches of any material will serve as an adequate insulator.

3. The rubber tires on an automobile are what protects a person from lightning injury. False. See number 2. Electrical energy travels along the outside of a metal conductor (the car body) and dissipates through the rainwater to the ground or off the axles or bumper of the car.

4. Wearing metal around the head or as cleats on shoes will increase the risk or “attract” lightning. False. There is no evidence to support this. Lightning victims often receive the
impact of a nearby strike as the current traveling across the ground. The current then comes up through the feet, sometimes causing shoes to be blown off. As the current travels across the skin, metal objects along the way are heated as an effect of the strike, but never because they caused or attracted the strike.

5. Carrying an umbrella increases the risk. This is somewhat true if a person’s height becomes greater by holding an umbrella but provides an insignificant effect.

6. Lightning always hits the highest object. False. Lightning only “sees” objects about 30 to 50 meters (90 to 150 feet) from its tip. In addition, several pictures exist of lightning hitting halfway down a flagpole or striking in a parking lot next to light poles. Someone standing in the middle of a football field will not be protected by the goalposts if lightning is coming down over his head. Similarly, there are many photographs of lightning branching to meet the earth in several places.

7. There is no danger of lightning injury unless it is raining. False. Although lightning only occurs as a result of thunderstorms, it can travel 16 km (10 miles) or more in front of the thundercloud to strike a person or object long before the rain comes down. Nearly 10% of lightning occurs when there is no rain falling in the area of the strike. It has also been known to reach over a mountain range and hit “out of the blue” from the thunderstorm that was on the other side of the peak and was neither visible nor audible to the victim.

8. Lightning may occur without thunder. False. Whenever there is lightning, there is thunder, and vice versa. Sometimes it will appear that there is lightning without thunder because thunder is seldom heard more than 16 km (10 miles) from the lightning stroke or may be blocked by buildings or mountains. In addition, survivors who are very close to the strike may not hear the thunder.

INCIDENCE OF INJURY

Spatial Distribution of Lightning in the United States

The distribution of cloud-to-ground lightning across the United States is well known because of the operation of real-time lightning detection networks. On average, more than 20 million cloud-to-ground flashes are detected each year in the United States. [130,164] On a shorter time scale, more than 50,000 flashes per hour are sometimes detected during summer afternoons over the United States. [13] Existing technology provides detection of at least 90% of all cloud-to-ground flashes within the contiguous United States.

A multiyear climatology of lightning from detection network data shows that central Florida has the greatest number of flashes per area in a given year (Fig. 3-1A). Flash density decreases to the north and west from there. Flash densities over Missouri, Iowa, and Illinois during the 1993 Mississippi River flood rivaled those over Florida. [13] In addition to the general features in Figure 3-1, important local variations occur along the coast of the Gulf of Mexico, where sea breezes enhance lightning frequency. [14,153]

Additional important maxima and minima are found in and around the regions in the western United States with mountains and large slopes in terrain. [14,149]

Lightning Around the World

Lightning detection systems similar to the U.S. network have been installed over part or all of more than 40 countries on every continent except Antarctica. Some of these ground-based networks have been in operation for up to 2 decades. However, there is no compilation of cloud-to-ground lightning flashes from such networks covering more than one country at a time. In the last decade, ground-based systems have been developed and deployed that detect the full horizontal and vertical extent of flashes. [17] Flashes detected with such systems are identified as three-dimensional, cloud, in-cloud, or total lightning. Total lightning networks have shown that five or more cloud flashes occur for every cloud-to-ground flash, and cloud flashes can have horizontal extents of 161 km (100 miles) or more. Total lightning networks sometimes show that cloud-to-ground flashes are connected to a complex lightning structure. Cloud flashes do not directly affect people on the ground. However, their wide range of relationships with ground flashes makes understanding ground strikes somewhat more complex than had been the case before these data became available. No ground-based maps of total lightning have been developed to date. However, a general view of worldwide total lightning activity as detected by the satellite-borne Lightning Imaging Sensor (LIS), which measures both cloud-to-ground and cloud flashes, is shown by Figure 3-1B.

Most lightning occurs over tropical and subtropical continents. There is far more lightning over land than over the oceans. Some flash frequencies in South America, southeast Asia, and especially equatorial Africa are much greater than found in the United States over Florida and other Gulf Coast locations. In some tropical and subtropical regions, maximum lightning density during the year is influenced primarily by the monsoon and coincides generally with the months of heaviest rainfall (Table 3-1).

Temporal Distribution of Lightning in the United States

Lightning is most common in summer months (Fig. 3-2A). About two thirds of flashes occur in June, July, and August. In the southeastern states, lightning occurs quite often during all months of the year. A primary ingredient for lightning formation is a significant amount of moisture in the lower and middle levels of the atmosphere; this fuel for thunderstorms is consistently found in humid subtropical and tropical regions. The other necessary ingredient to produce a thunderstorm is a mechanism to lift the moisture. Along coastlines and mountain slopes during the summer months, updrafts are produced almost daily that provide favored locations for frequent thunderstorms.

Lightning is most common in the afternoon (see Figure 3-2B). [152] Nearly half of all lightning occurs from 1:00 through 3:00 local standard time (LST). Figure 3-2B combines regional results during the summer in several regions of the United States. [140,141,149] Lightning is at a maximum in the afternoon because the updrafts necessary for thunderstorm formation are strongest during the hours of the day when surface temperatures are highest, resulting in the greatest vertical instability.

U.S. Lightning Casualties in Storm Data

Every month, each National Weather Service (NWS) office in the United States compiles a list of damaging or notable weather
Figure 3-1. A, Cloud-to-ground flashes per square kilometer per year in the United States from a network of lightning detection antennas from 1996 to 2000. B, Total flashes per square kilometer per year for the world from 12 April 1995 through 1999 from the Optical Transient Detector. (A courtesy Yaesula, Inc., Tucson, AZ; B courtesy Hugh Christian, NASA/ Marshall Space Flight Center.)

Table 3-1. Top 10 Areas of Lightning Density in the World Based on the Optical Transient Detector Satellite

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>FLASHES (km²/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kamembe, Rwanda</td>
<td>92.7</td>
</tr>
<tr>
<td>2. Boende, Democratic Republic of Congo</td>
<td>66.3</td>
</tr>
<tr>
<td>3. Lusambo, Democratic Republic of Congo</td>
<td>52.1</td>
</tr>
<tr>
<td>4. Kananga, Democratic Republic of Congo</td>
<td>50.3</td>
</tr>
<tr>
<td>5. Kuala Lumpur, Malaysia</td>
<td>48.3</td>
</tr>
<tr>
<td>6. Calabar, Nigeria</td>
<td>47.3</td>
</tr>
<tr>
<td>7. Franceville, Gabon</td>
<td>47.1</td>
</tr>
<tr>
<td>8. Posadas, Argentina</td>
<td>42.7</td>
</tr>
<tr>
<td>9. Ocana, Colombia</td>
<td>39.9</td>
</tr>
<tr>
<td>10. Concepcion, Paraguay</td>
<td>37.0</td>
</tr>
<tr>
<td>11. Orlando-Tampa, Florida</td>
<td>35.4</td>
</tr>
</tbody>
</table>

This list is sent to National Oceanic and Atmospheric Administration (NOAA) headquarters and then to NOAA’s National Climatic Data Center (NCDC) in Asheville, NC. These lists are combined at NCDC, and then Storm Data is published.

Since 1974, Storm Data has reported an average of 67 deaths per year from lightning. Table 3-2 shows that lightning was second only to flash floods and floods in weather-related deaths during the 30 years since 1974. Lightning-related casualties and damages are often less spectacular and more dispersed in time and space than other weather phenomena. Therefore, lightning deaths, injuries, and damages have been found to be underreported. Factors contributing to the underreporting include the fact that most casualty events involve only one person or object, the NWS only uses newspaper clipping services to compile Storm Data, there is a lack of a uniformly applied definition of lightning versus lightning-related deaths, and there is inconsistency in listing medical diagnoses.
Likewise, nonfatal injuries are also underreported. Even though some studies have shown a mortality rate as high as 20% to 30%, these were retrospective reviews of the medical literature, which tended to overreport more severe injuries. In a thorough search of Colorado hospital and emergency department visits, Cherington and coworkers found that a ratio of 10 injuries to every death was probably more reasonable. There are additional injuries to persons whose visits are not reported by a medical facility or who do not seek immediate treatment.

Even though Storm Data includes many property damage reports caused by lightning, it represents an extremely small portion of the actual total. Each Storm Data report has some or all of the following: year, month, day, time, state, and country, as well as number, gender, and location of fatalities and injuries, and amount and type of damage. Despite its underreporting of lightning impacts and sometimes incomplete nature, Storm Data is a consistent national data source concerning weather impacts across several decades and is likely the best system in the world for collecting weather-related hazard information.

**Distributions of Lightning Deaths by State**

Lightning casualty deaths in the United States by state from 1990 to 2003 are shown in Figure 3-3A. The general pattern

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Flash</td>
<td>107</td>
<td>86</td>
<td>70</td>
</tr>
<tr>
<td>Lightning</td>
<td>67</td>
<td>43</td>
<td>236</td>
</tr>
<tr>
<td>Tornado</td>
<td>63</td>
<td>34</td>
<td>108</td>
</tr>
<tr>
<td>Tropical cyclone</td>
<td>14</td>
<td>14</td>
<td>233</td>
</tr>
<tr>
<td>Marine</td>
<td>14</td>
<td>55</td>
<td>53</td>
</tr>
<tr>
<td>Winter</td>
<td>37</td>
<td>36</td>
<td>174</td>
</tr>
<tr>
<td>Heat</td>
<td>37</td>
<td>36</td>
<td>174</td>
</tr>
<tr>
<td>High wind</td>
<td>24</td>
<td>24</td>
<td>136</td>
</tr>
<tr>
<td>Cold</td>
<td>20</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Thunderstorm wind</td>
<td>19</td>
<td>19</td>
<td>226</td>
</tr>
<tr>
<td>Mud slide</td>
<td>15</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Hail</td>
<td>0</td>
<td>0</td>
<td>121</td>
</tr>
<tr>
<td>Other</td>
<td>35</td>
<td>35</td>
<td>419</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>253</strong></td>
<td><strong>438</strong></td>
<td><strong>2924</strong></td>
</tr>
</tbody>
</table>

Order is by deaths from storm types with 30-year records, then by 2003 deaths from other natural hazards. Source: www.nws.noaa.gov/om/hazstats.shtml.

References 48, 74, 82, 83, 86, 94, 109, 127, 142, 147, 152, 165.
Figure 3.3. Rank of each state in lightning deaths from 1995 to 2004. A, Deaths per state. B, Deaths weighted by state population. (Updated from Curran EB, Holle RL, López RE. J Climate 13:3448, 2000, with permission.)
has similarities to the distribution of lightning in Figure 3-1, but Florida has twice as many deaths as any other state. Many of the other high numbers of fatalities are from populous states. It is preferable to use deaths for these results because the number of injuries is somewhat unevenly collected.

The lightning hazard is shown better when population is taken into account (see Figure 3-3B). The maximum rate of lightning fatalities shifts away from the more populous states, mainly in the eastern part of the country, to the Rocky Mountain and Great Plains states. Some southeastern states often have high rankings in both deaths and death rates (see Figure 3-3). The only states in the top 10 of both fatality and fatality rate are Florida, Colorado, Alabama, and Louisiana. Detailed state listings of deaths and injuries, and their rates, from 1959 to 1994, are in Curran and coworkers.74

Two U.S. lightning fatality studies had similar results to Figure 3-3 for earlier time periods. Duclos and Sanderson52 used data from the National Center for Health Statistics, and Mogil and coworkers52 used Storm Data. Single-state maps by county were compiled for Florida,42,83 North Carolina,12 Michigan,66 and Colorado.162,164 Outside the United States, studies showing the spatial distribution of fatalities by political boundaries have been developed for Canada,166 Singapore,142 Australia,14 and France.83 Many additional studies have included national totals over periods from several to many years.

**Monthly Variations of U.S. Casualties**

By month, lightning casualties peak during July (see Figure 3-2C). The percentages increase gradually before July, then decline more quickly after the maximum. Cloud-to-ground flashes show similar features (see Figure 3-2A). Summer maps of lightning casualty rates in works by Curran and coworkers74 are similar to annual maps. During other seasons, casualty rates are higher in southern states. Casualty rates in the northeast are low except during the summer, whereas they are highest on the West Coast during autumn and winter.

A July maximum was also found in prior Storm Data studies, as well as a slower increase before and a faster decrease after July.82,83,86,142,147,152 August maxima were found in Florida by Duclos and coworkers and Holle and coworkers.107 Away from the tropics, most casualties occur during summer months. For example, January has the largest number of Australian fatalities due to the reversal of seasons from the Northern Hemisphere.48 In the equatorial location of Singapore, fatality maxima in November and April are similar to the annual cycle of local thunderstorms.165

**Time-of-Day Variations of U.S. Casualties**

Most lightning casualties occur in the afternoon (see Figure 3-2D), two thirds occur between 1200 and 1800 LST. They show a steady increase toward a maximum at 1600 LST, followed by a slower decrease after the maximum. Lightning flashes in Figure 3-2B showed a faster increase to the afternoon maximum than shown for casualties. Lightning occurs most often in the afternoon because the ground is heated most strongly by the sun during that time period. As a result, vertical cumulus clouds form and produce lightning when they are tall enough to have tops colder than freezing temperatures. Narrower distributions of casualties centered in the afternoon are apparent in the Rockies, Southeast, and Northeast compared with the broader time series in the plains and Midwest.72

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>DEATHS (%)</th>
<th>INJURIES (%)</th>
<th>CASUALTIES (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>84</td>
<td>82</td>
<td>83</td>
</tr>
<tr>
<td>One victim per event</td>
<td>91</td>
<td>68</td>
<td>68</td>
</tr>
</tbody>
</table>

In the evening and at night (1800 to 0559 LST), casualties are most frequent in the plains, upper Midwest, and some populous eastern states.74 More than half of the deaths from 0000 to 0559 LST occurred when people were in a house set on fire by lightning, and 21% occurred when people were camping in tents.

Outside of the summer months, lightning casualties are distributed more widely through the day. Lightning is less concentrated during the afternoon in those months because the ground is not heated as much as in summer. As a result, more thunderstorms are formed by large-scale traveling disturbances during all hours of the day and night.

Maximum lightning impacts from 1400 to 1600 LST were documented by Duclos and Sanderson,82 Ferretti and Ojala,84 and López and Holle.147 Duclos and Sanderson62 found an 1800 LST peak in North Carolina deaths.

**Gender and Number of Casualties**

Table 3-3 shows that males are much more frequent lightning casualties than are females. Similar ratios were found in the U.S.,82,83,105,112,114 Singapore,19,14 and England and Wales.19 During the recreation activities of soccer, baseball, golf, and camping, the male percentage of casualties was as low as 57% during camping to 94% during golf.107 The camping rate was 76% male, if a South Africa event with 23 Girl Scouts and adult leaders is omitted.126

The most common situation was for only one victim to be involved in a lightning incident. This is an important contributor to the underreporting of lightning casualties.144 The largest single death total in one U.S. event resulted from the 1963 crash of an airliner in Maryland that killed 81 people. The largest number of injuries at one event was 90 at a Michigan campground.106 The same tendency for single victims was noted in the United States,147 Singapore,165 and Australia.48

**20th Century Trends in U.S. Lightning Deaths**

The number of lightning deaths reported since 1900 is shown in Figure 3-4A. During the first 20 years, annual reported deaths increased from less than 100 to about 450 because of an increase in reporting states. During the 1920s and 1930s there were about 400 lightning deaths per year, whereas recently it has been less than 75 per year. There has been a persistent drop in deaths since 1944. The same dramatic decline since 1940 was noted by others.82,152

The effect of changes in population is taken into account by dividing by the population. Figure 3-4B shows lightning deaths per million people per year. In the earlier part of the series, year-to-year fluctuations are relatively large as reporting states with different demographic and climatic conditions were included. Since 1925, the fluctuations are consistently smaller and more
regular as the death rate decreases. The normalized time series indicates a decrease during the 20th century from more than six at the start to as low as 0.4 deaths per million people late in the century.

Notable decreases in deaths were also documented with long-term data sets in England and Wales, England and Wales compared with Australia, and Singapore. Australian deaths increased during the years 1825 to 1918, then decreased through 1991.

**Effect of Rural-to-Urban Migration**

Before the turn of the last century, lightning deaths appeared to occur often in rural settings. Since then, the percentage of the U.S. population in rural areas has dramatically decreased. Figure 3-4B shows that the percentage of the population living in rural areas since 1890 decreased from 60% in 1900 to 25% in 1990. Departures from the exponential decrease are seen as a slowing in the 1930s and early 1940s during the Great Depression, and an acceleration of the trend in the 1950s and 1960s with increased urbanization after World War II and the Korean War. The adjusted normalized lightning-death plot is superimposed on the rural population curve in Figure 3-4B. The remarkable agreement leads to a conclusion that the decrease in population-adjusted deaths is closely related to the relative reduction in rural population. This link between long-term decreases in both lightning deaths and rural population has been hypothesized, as well as being attributed to improved home electrical systems that include substantial grounding, and improved medical treatment and communications, education, and meteorologic warnings. This trend has been replicated with normalized population data from Canada and Spain. The trend toward fewer lightning deaths in the United States since 1959 is divided into three segments in Fig. 3-5, which shows a steady decrease in fatality rate from 1959 to 1978, and two populations of lower fatality rates in the 1980s and since 1991. There were 20% more deaths reported in the National Center for Health Statistics than in Storm Data. The most recent decreases could correspond with efforts in lightning safety edu-

*References 62, 64, 65, 82, 105, 135, 136, 143–145, 147, 152.

**Types of Lightning Casualty Incidents**

The preceding analyses suggest a link between the shift from rural to urban settings and the number of lightning casualties. Kreutzer documented lightning deaths and injuries from 1891 to 1894, and an analysis was made of entries in Storm Data 100 years later (Fig. 3-6).

In the 1890s, rural deaths were much more frequent than urban. Indoor fatalities were the most frequent; 23% of all deaths were inside houses. The next largest type were outdoors and agricultural incidents, whereas recreation and sports incidents were virtually nonexistent.

In the 1990s, rural settings and agricultural incidents were much less frequent. Only 2% of modern deaths were attributed...
Worldwide Lightning Fatalities

Extrapolation of these results to the world can be considered with caution. The U.S. lightning death rate early in the 20th century exceeded 6 deaths per million people (see Figure 3-4B), whereas the rate is now less than 1 death per million. Earlier lightning deaths often occurred in agricultural incidents in rural settings or inside buildings before widespread installation of wiring and plumbing. The recent rates also can be considered typical of much of Europe and other industrialized, urbanized countries.

However, many people in the populous tropical and subtropical areas of Africa, South America, and Southeast Asia, including China and the Indian subcontinent, continue to rely on labor-intensive agriculture and live in dwellings with minimal or no grounding, and are serviced by less-developed infrastructures for medical response and meteorologic information. The earlier rates from the United States could be considered to be appropriate in these regions, where lightning is generally as frequent as in the United States. In fact, some of these areas have higher flash densities than the Florida maximum in the United States (see Table 3-1). Although there is almost no systematic information on lightning deaths in these regions, frequent reports of multiple lightning casualties per event show that rural and agricultural events continue to be dominant settings of casualties, together with some recreational cases involving soccer. When these regions with a population of more than 4 billion people are considered, and the rate of 6 deaths per million people per year is applied, a total of 24,000 lightning deaths per year is obtained. If the ratio of 10 injuries for every death is applied, 240,000 people are injured by lightning per year in these regions.

EARLY SCIENTIFIC STUDIES AND INVENTION OF THE LIGHTNING ROD

The study of electric phenomena is often traced to the publication of Gilbert’s De Magnete in London in 1600. Experiments in France and Germany and by members of the Royal Society of London led to the invention of the Leyden jar in 1745.

Benjamin Franklin is generally regarded as the father of electric science and during his lifetime was known as the American Newton. The reason he was accepted into the French and English courts around the time of the American Revolution was not because he was an ambassador from America but because he was considered to be one of the foremost scientists of his time. Franklin was elected to every major scientific society at the time and received medals of honor from France and England for his scientific contributions.

Before his work, it was thought that two distinct types of electric phenomena existed. Franklin’s work unified these two forces, and he is responsible for renaming them as positive and negative charges. He also proved with numerous experiments that lightning was an electric phenomenon and that thunderclouds are electrically charged, as demonstrated by the famous kite and key experiment. He invented the lightning rod and announced its use in 1753 in Poor Richard’s Almanack:

It has pleased God in His Goodness to Mankind, at length to discover to them the Means of securing their Habitation and other Buildings from Mischief by Thunder and Lightning. The Method is this: Provide a small Iron Rod (It may be made of the Rod-iron used by the Nailers) but of such a Length, that one End being
three or four Feet in the moist Ground, the other may be six or eight Feet above the highest Part of the Building. To the upper End of the Rod fasten a Foot of brass Wire the Size of a common Knitting-needle, sharpened to a fine Point; the Rod may be secured to the House by a few small Staples. If the House or Barn be long, there may be a Rod and Point at each End, and a middling Wire along the Ridge from one to the other. A House thus furnished will not be damaged by Lightning, it being attracted to the Points, and passing thro the Metal into the Ground without hurting any Thing. Vessels also, having a sharp pointed rod fix’d on the Tops of their Masts, with a Wire from the Foot of the Rod reaching down, round one of the Shroods, to the Water, will not be hurt by Lightning.

In the 1750s and 1760s, the use of lightning rods became prevalent in the United States for protection of buildings and ships. Some scientists in Europe urged the installation of lightning rods on government buildings, churches, and other tall buildings. However, religious advocates maintained that it would be blasphemy to install such devices on church steeples, in that the churches received divine protection. Because of this divine protection, some towns chose to store munitions in their churches, leading on more than one occasion to significant destruction and loss of life when the churches were hit by lightning.

Part of the delay in installing lightning rods in England may have been due to British distrust of the scientific theories originating in the upstart, newly independent United States. Years and numerous unsuccessful trials with English designs were required before the Franklin rod became accepted on Her Majesty’s ships and buildings.

At one time, lightning rods were theorized to be diffusers of electric charges that could neutralize a storm cloud passing overhead, thus averting a lightning stroke. This theory was in part an outgrowth of the observation of St. Elmo’s fire, an aura appearing around the tip of lightning rods and ships’ masts during a thunderstorm. This phenomenon is caused by an electron discharge that results from the strong electromagnetic field induced around the glowing object.

Properly installed lightning rods and lightning protection systems do not “attract” lightning, but rather protect a building by allowing the current from a lightning strike that would have occurred, regardless of the protection system, to flow harmlessly through the system to the ground instead of into or through the building, which often causes more extensive damage. It has not been uncommon for charlatans to take advantage of the fear of lightning and the danger of lightning-caused fires. In the past, they drove from farm to farm offering to “discharge” the lightning rods on barns and homes for a fee.

Lightning protection still remains an area of controversy, with only some of the lightning codes and protective devices verified by objective research. Some of the recent codes (written by the lightning protection industry) now do more to protect buildings and shelters but unfortunately may actually increase the risk for those seeking “shelter” in bus, pool, rain, or golf types of structures, not only by increasing the chances of side-flash from lightning protection downconductors, but also by increasing the sheltered person’s effective height. Systems that claim to “predict” where and when lightning may strike an object, rather than detect the flash, have yet to have the scientific validity of their technology proven. The public is recommended to follow the caveat emptor principle, whether it applies to protection of shelters or detection and prediction of lightning. It remains salutary that the most effective protection still centers around the simple Franklin rod.

The first Lightning Rod Conference was held in London in 1882. Recommendations from this conference were published that year and again in 1905. Further progress in the study of the properties of lightning came with development of Sir Charles Vernon Boy’s rotating camera and Dufour’s high-speed cathode ray oscillograph, which helped delineate physical properties of lightning, including direction and speed of the strokes.

Certain countries developed codes of practice for lightning protection (Germany, 1924; United States, 1929; Britain, 1943; British colonies, 1965). A variety of materials, including copper, aluminum, and iron, are recommended by these codes, which also specify the measurements and construction of the protective system, depending on the height, location, and construction of the structure to be protected. The most recent U.S. code revision was the National Fire Protection Act of 2004, written by lightning protection practitioners. Lightning strokes vary in power and frequency, depending on terrain and geographic location. Complicated formulas have been devised to take into account relative frequency of strikes in an area; height, construction, and design of the building; and degree of protection desired, depending on whether it is a storage shed, house, school, hospital, or munitions factory.

A lightning protection system should be designed to take into account these factors plus the economic considerations of construction. Including a system in the initial design and construction is always easier and less expensive than modifying a completed building. In addition, except where required by code, the owner may decide that a lightning protection system is not worth the expense, for example, for a mountain retreat that is seldom visited. An excellent noncommercial source for discussion of these risks is www.lightningsafety.com.

PHYSICS OF LIGHTNING STROKE

Lightning Discharge

The study of lightning discharge and formation is extremely complex and involves an entire branch of physics and meteorology. We therefore illustrate here the simplified and most common mechanism of thundercloud formation and lightning strike.

Thunderstorms can be created by a number of factors that produce vertical updrafts. These ingredients are usually caused by cold fronts, large-scale upward motions, sea and lake breezes, lifting by mountains, and afternoon heating of warm, moist air (Fig. 3-7A).

As warm air rises, turbulence and induced friction cause complex redistribution of charges within the cloud (see Figure 3-7B). Water droplets and ice crystals within the cloud acquire and increase their individual charges. A complex layering of charges, with large potential differences between the layers, results from the interaction between charged particles and internal and external electrical fields within the cloud.

Generally, lower layers of the thundercloud become negatively charged relative to the earth, particularly when the storm occurs over a flat surface. The earth, which normally is negatively charged relative to the atmosphere, has a strong positive
charge induced as the negatively charged thunderstorm passes overhead. The induced positive charge tends to flow as an upward current into trees, tall buildings, or people in the area of the thunderscorp cloud and may actually course upward as "upward streamers."\footnote{1,6}

Normally, discharge of the potential difference is discouraged by the strong insulatory nature of air. However, when the potential difference between charges within the clouds or between the thundercloud and ground becomes sufficient, the intervening air may break down under the influence of the electric field created and the charge may be dissipated as lightning.

A lightning stroke begins as a relatively weak and slow downward leader from the cloud (see Figure 3-7C). Although the tip of the leader may be luminous, the stepped leader itself is barely discernible with the unassisted eye. The leader travels at about one-third the speed of light (1 × 10^6 m/sec), and the potential difference between the tip and the earth ranges from 10 to 200 million volts. The leader ionizes a pathway that contains superheated ions, both positive and negative, thus forming a plasma column of very low resistance. It travels with relatively short branched steps, going down about 50 m (150 feet) and then retreating upward. The next time it goes down, it fills the

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Figure 3-7. A, Air rises and condenses into a cumulonimbus cloud. B, Typical anvil-shaped thundercloud. C, Water droplets within the cloud accumulate and layer charges. D, Stepped downward leader initiates the lightning stroke. E, Positive upward streamer rises from the ground to meet the stepped leader. F, Return stroke travels back up the channel made by the stepped leader.
original ionized path but branches at the end to go down another 50 m (150 feet) and then retreat again. This up-and-down, polybranching process continues until the leader comes to within 30 to 50 m (100 to 150 feet) of the ground. Because lightning follows this ionized path, its tip “sees” only objects within about a 30- to 50-m (100- to 150-foot) radius, meaning that the hill or tower 60 m (200 feet) away from a person will not be “seen” by the lightning as a potential target.

As the tip of the lightning gets closer to the earth with the large potential at its tip (Fig. 3-7D), more concentrated areas of induced charge accumulate on the earth, particularly at the peaks of tall, relatively sharp objects. Several upward streamers (see Figure 3-7E) may rise vertically from these objects toward the downward leader head. Ultimately one, or a small number, of the upward streamers will contact the downward leader, thus completing a lightning channel of low resistance between cloud and ground. The process of the downward leader joining with the upward streamers is called attachment and occurs when the tip of the stepped leader is within the “striking distance” of the point of attachment. There is often more than one point of attachment to the ground.125

As the low-resistance channel is formed by attachment, the potential difference between cloud and ground effectively disappears and the energy available is dissipated in an avalanche of charge between cloud and ground. This avalanche is referred to as the return stroke (see Figure 3-7F) and is highly luminous. Lightning is therefore a current, or charge dumping, phenomenon rather than a voltage phenomenon, and is analyzed accordingly. Subsequent to the discharge through the return stroke, the channel remains attached for a small amount of time, and with quick redistribution of charge from other regions of the cloud to the top of the channel (via J- and K-intracloud streamers), further return strokes may occur. A lightning flash may be made up of multiple strokes (1 to 30, mean 4 to 5) and is perceived by the eye as flickering of the main channel.

When a very tall building is involved, or when high mountains rise into the clouds, the leader stroke may initiate from the building or mountain rather than from the cloud. In such cases, a joining stroke is rarely seen initiating from the cloud. The channel of ions formed by the leader stroke is maintained as a continuous stroke, as the return stroke (misnamed in this instance) travels in the same direction from the ground or object to the cloud, dissipating the charge difference.

The tip of the downward leader is the most luminous of the sequence of strokes in each lightning discharge, in that a huge amount of energy must be expended to overcome air resistance and ionize a channel. Because of the relative slowness and brilliance of the leader, lightning is perceived as traveling from the cloud to the earth, although the vast majority of energy is actually dissipated in the opposite direction with the return strokes. The direction of the return stroke is not visually perceived because of its tremendous speed and is recognized merely as an instantaneous brightening or flickering of the ionized pathway. Lightning may vary in apparent color due to the amount and type of particles in the air between the observer and the lightning channel, from the excitation of nitrogen atoms in the atmosphere, or because the particles of dust through which the lightning passes are high in ion or mineral content.

**Diameter and Temperature of Lightning**

Many techniques could be used to measure the diameter or temperature of the lightning stroke. Unfortunately, all measurement techniques have artifact problems. Visual measurement of the stroke using standard photography usually shows the diameter of the main body of the stroke to be about 2 to 3 cm.

The diameter of the arc channel is sometimes measured indirectly, using measurements of holes and strips of damage that lightning produces when it hits aluminum airplane wings, buildings, or trees. Measurements vary from 0.003 to 8 cm, depending on the material destroyed, with hard metallic structures sustaining smaller punctures than do relatively softer objects, such as trees. The ionized sheath around the tip of the bright leader stroke has never been measured but is estimated to be 3 to 20 m (10 to 66 feet) in diameter.

The temperature of the lightning stroke varies with the diameter of the stroke and has been calculated to be about 8000°C (14,000°F). Others estimate the temperature to be as high as 20,000°C (36,000°F). In a few milliseconds the temperature falls to 2000° to 3000°C (3600° to 5400°F), that of a normal high-voltage electric arc.

**Forms of Lightning**

Lightning can be divided into cloud-to-ground and cloud (intracloud) flashes (Fig. 3-8). Cloud-to-ground flashes contact the surface of the earth at one or more locations, depending on the number and type of return strokes. Cloud lightning can travel between clouds, within clouds, from cloud to cloud, and in all combinations of these paths. The same flash can both (1) strike the ground at one or more places and (2) travel a long distance in clouds. Numerous single continuous flashes lasting 1 to 2 seconds have been measured to exceed 100 km (62 miles) in length.147 There are several times as many cloud flashes as reach the ground. From the point of view of a person on the ground, cloud flashes may appear to travel in long lines streaking across the sky, or be totally within the clouds.

The most unusual, least understood, and least predictable type of lightning is ball lightning.187 Ball lightning is usually described as a softball-sized orange to white globe. It may enter a plane, ship, or house, travel down the hallway, injure some people and objects and not others that it encounters, and exit

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**Figure 3-8.** Example of cloud-to-ground and cloud lightning. (From Krider EP, Ladd GC: Weather 30(3):77–81, 1975, with permission.)
out another door, chimney, or window, explode with a loud bang, or exhibit other bizarre behavior.\textsuperscript{12,14,18,50,90}

Lightning may be either positive or negative in charge.\textsuperscript{171} Cloud-to-ground lightning flashes usually lower negative charge to ground. Positive cloud-to-ground flashes tend to occur during the winter, at the end of thunderstorms, and in relatively shallow thunderstorms. It is not known if positive lightning has a different injury profile. Positive lightning may be more likely to occur when there is particular matter in the air, including smoke from forest fires. Laboratory positive flashes are more erratic than negative flashes.

**Thunder**\textsuperscript{91,104,187,189}

Thunder is formed when shock waves result from the almost explosive expansion of air heated and ionized by the lightning stroke.\textsuperscript{91,187} The following are accepted statements:

1. Cloud-to-ground lightning flashes produce the loudest thunder.
2. Thunder is seldom heard over distances greater than 16 km (10 miles).
3. The time interval between the perception of lightning and the first sound of thunder can be used to estimate distance from the lightning stroke.
4. Atmospheric turbulence reduces audibility of the thunder.
5. Wind, rain, manmade noise, and vegetation, as well as hills and mountains, can reduce audibility of the thunder.
6. The pitch of thunder deepens as the rumble persists.

The thunder clap from a close lightning flash is heard as a sharp crack. Distant thunder rumbles as the sound waves are reflected and modified by the thunderstorm's turbulence.\textsuperscript{187} Because there is a large difference between the speed of light and the speed of sound, the distance to lightning can be estimated by a person on the ground. The estimation is made by the flash-to-bang method of counting the seconds between seeing a flash and hearing the thunder from the same flash. The time interval between light and thunder is 5 seconds per mile, which is the same as 3 seconds per kilometer.\textsuperscript{104,189} For example, if the difference is 30 seconds from when a flash is seen until its thunder is heard, the flash is 6 miles away (10 km). This distance is found by taking the fact that thunder travels a mile every 5 seconds, so a flash that is 6 miles away takes 30 seconds to reach an observer.

### MECHANISMS OF INJURY BY LIGHTNING\textsuperscript{5,12,28,56}

#### Concepts in Electrical Mechanisms

A voltage can be applied to a body. It can be regarded as the pressure applied to a body to force it to conduct electric current, like water pressure applied at one end of a pipe to cause water flow. It is an external force, and after it is applied, a current (amps) flows as a result through the body, like the water in the pipe. The amount of current is inversely proportional to the resistance of the body, that is, for a given applied voltage, the higher the resistance of the body, the smaller the resulting current.

Resistance is a given property of a body. A piece of metal has a predictable and exact resistance, for our purposes invariable. It might be thought of as analogous to the diameter of the water pipe, or friction within the pipe. The resistances of various tissues have been measured and characterized as properties of the tissues concerned. If it is assumed that resistance is predictable, then resistance, voltage, and current can be related linearly, making modeling possible. Voltage, current, and resistance are related by Ohm's law. However, tissue resistance is not constant, but is affected by a number of factors that do not depart from the principles of linear analysis. Alterations in tissue resistance are predictable, so analysis can proceed on a "piece-wise linear" basis.

Alternatively, if a current is forced to flow through a body of a given resistance, as is the case with lightning, a voltage directly proportional to the resistance of the body can be measured across the body. That is, for a given current forced through a body, the higher its resistance, the higher will be the measured voltage. The relationship is governed by Ohm's law. The terms voltage and potential tend to be used interchangeably.

The remaining concept is that of an electric field. If we consider an air gap, we can apply a voltage to that air gap. Air has a known resistance, which is generally high. Thus all one conducts is a tiny current. In time, the air "breaks down," and an avalanche of current flows across the gap. A large noisy flashover is the observed result. When in time this occurs varies with the voltage applied and the width of the gap, whether it is electrical charge built up from walking across a carpet in the winter or the electrical energy built up in a cloud. The gap is submitted to the electrical stress of an electric field. The electric field is defined as the voltage across the gap divided by its width. Flashover in air occurs at about 4000 V/cm or 10,000 V/inch.

### Electrical Mechanisms of Injury

Lightning is dangerous because of electrical effects, heat production, and concussive force. In addition, lightning may injure indirectly via forest fires, house fires, explosions, or falling objects such as trees. Only injuries directly caused by lightning are discussed here.

Many factors contribute to how lightning injures a person, and there may be interplay between these at any given time. Exact prediction in an individual case is impossible.

The later discussion on pathophysiology states that, when lightning current is injected into an individual, the current is initially transmitted directly through the individual. Then, as internal structures (capacitances) charge, flashover occurs over the surface of the individual, and internal current reduces dramatically.\textsuperscript{19,122,143} Lightning current may initially be inflicted on a person in one of several ways, described in more detail later (Box 3-2 and Fig. 3-9). In each of these mechanisms, the processes indicated by Krigawa and coworkers can occur.\textsuperscript{19,122}

#### Box 3-2. Mechanisms of Lightning Injury

- Direct strike
- Contact potential
- Side flash, sometimes called “flash”
- Step voltage (EPR)\textsuperscript{195}
- Ground current
- Surface arcing
- Upward streamer current\textsuperscript{198}
- Blunt or concussive injury
Figure 3-9 cont'd. D. Earth potential rise. E. Upward streamer.
1. The internal current phase may be the most causative for the development of cardiac arrest and respiratory arrest.

2. As the body potential builds up in response to the current, it produces an electric field over the surface of the body. At a certain level (about one-half the air breakdown field of 4000 V/cm [10,000 V/inch]), current can emerge or escape by the body at various points of the body surface (also documented by Darveniza, *Electrical Properties of Wood and Line Design*). Metal pieces on the body trigger and enhance these surface discharges and surface flashovers.

3. As the current continues to increase, the surface flashover bridges the strike point and the ground. At this level, most of the lighting current flows as an arc current through the air outside the body (flashover effect). Only a very low fraction travels through the body at this point and may be too little to cause cardiac and respiratory arrest.

A direct strike occurs when the lightning stroke attaches directly to the victim (Fig. 3-9A). This is most likely in the open when a person has been unable to find a safer location, and probably occurs no more often than in 3% to 5% of injuries. Even though it seems intuitive that direct strike might be the most likely to cause fatalities, this has not been shown in any studies.

Contact, or touch potential, injury occurs when the person is touching or holding onto an object to which lightning attaches. A voltage gradient is set up on that object from strike point to ground, and the individual in contact with the object is subject to the voltage between their contact point and the earth (see Figure 3-9B). A current therefore flows through them. Contact injury probably occurs in about 1% to 2% of injuries.

A more frequent cause of injury, perhaps as much as 30% to 35%, is a side flash, also termed “splash.” Side flashes occur when lightning has hit an object such as a tree or building travels partly down that object before a portion “jumps” to a nearby victim (see Figure 3-9C). Standing under or close to trees and other tall objects is a very common way in which people are splashed. Current divides itself between the two paths in inverse proportion to their resistances. The resistance of the “jump” path represents an additional path separate from the path to the earth from the striking object. Side flash may also occur from person to person.

Earth potential rise (EPR) occurs because the earth, modeled ideally as a perfect conductor, is not so in reality. When lightning current is injected into the earth, it travels through the earth just like it would in any other conductor. Earth has a finite resistance, and so voltages are set up in the ground, decreasing in size with distance from the strike point. The voltage (or potential) of the earth is raised, hence the term EPR.

There are several consequences of EPR. If a person is standing in an area where EPR is active, that is, near the base of a strike, a voltage will appear between their feet and current will flow via the legs into the lower part of the body. This is more significant between front and back legs of animals, where the path may involve the heart (see Figure 3-9D).

A special case occurs when a person is injured inside a building as lightning hits nearby and is transmitted through the land line of the telephone, the pipes of plumbing and faucet handles, via electrical wiring as one uses a computer, or attempts to dispatch an ambulance. This is caused, for example, when the person, along with the environment around them, is raised to a potential via EPR. If the telephone line is not locally earthed (grounded), it is at the same voltage as the environment. The fact that the line is earthed remotely away from the local EPR environment causes the person to be subjected to a shock with current flowing between the local earth at high potential and the distant unaffected earth. This highlights that local electrical apparatus, including telephones, should be well grounded locally. The grounds of all local structures (power, telephone, plumbing, structural steel) should have a common grounding point (i.e., be bonded) to eliminate any voltage differences developing between separated ground points for each system. For the special case of indoor or telephone injury, EPR may account for 80% or more of the injuries.

Static electrical discharges may occur when a person reaches for a car door or stands close to a metal window or door frame in a thunderstorm, because the surrounding electrical field induces static electrical charges. These are not lightning injuries. While people may be startled when this happens, these discharges are unlikely to be any more dangerous than static discharges experienced in the winter months from shuffling across the carpet and reaching for a door handle.

Kitigawa has identified further subdivisions of the EPR phenomenon. He notes that not only can EPR occur as discussed, but it can also occur in a manner similar to the surface flashovers over a body, with arcs developing over a ground surface (Fig. 3-10). Despite modeling to the contrary, the grounding earth is not homogeneous and provides arc generation points.

Ground current effects are possibly more likely to be temporary, slight, and less likely to produce fatalities. However, multiple victims and injuries are frequent. Large groups have been injured on baseball fields, at racetracks, while hiking, and during military maneuvers. Shocks via telephones can produce significant long-term problems.

Irregularities are highlighted on mountainsides. If the terrain is markedly irregular, the spreading lightning current may reach the surface, and a surface arc discharge develops together with the flow of the conduction current in the ground. Because arcs carry considerable energy, a person exposed to a surface arc discharge is more likely to have a more severe effect, including thermal injuries, temporary paralysis, or even death. This mechanism of injury makes it particularly dangerous for someone on a mountainside to shelter inside a shallow cave or under a small cliff or outcropping of terrain where surface arcing is much more likely to occur, injuring the person just as they feel some degree of safety has been achieved (see Figure 3-9D3).

The danger of upward streamers has recently been documented. Injury may occur when a victim serves as the conduit for one of the usually multiple upward leaders induced by a downward stepped leader and its field (see Figure 3-9F). Streamers occur even when there is no attachment between them and the stepped leader. While one might think that these are weak in energy compared to the full lightning strike, and although upward leaders are poorly characterized, they may carry several hundred amperes of current to be transmitted through the victim. This mechanism has been mentioned by many engineering and physicist lightning experts in their writings, and a case report has been published in the medical literature. Upward streamer injury is probably a much underestimated mechanism of injury and may account for as much as 30% to 35% of injury cases.

Finally, persons may suffer from (non-electrical) blunt injury, either by being close to the concussive force of the shockwave produced as lightning strikes nearby or if ground current or...
some other mechanism induces an opisthotonic contraction. Victims have been witnessed to have been thrown tens of yards by either mechanism. In addition, some have theorized that a person struck by lightning may suffer from explosive and implosive forces created by the thunderclap, with resulting contusions and pressure injuries, including tympanic membrane rupture. Another mechanism of blunt injury is blast injury resulting from vaporization of water on the body surface from a surface flashover spark. Lightning blast injury to the skull, brain, and viscera has been elegantly demonstrated in animals.\textsuperscript{62}

Many cases of multiple injuries are likely a combination of many of these effects, with the majority of them from EPR and upward streamers, sometimes complicated by side flashes if people or animals are standing too close together (Figs. 3-11 and 3-12). Information on the exact mechanisms remain poorly documented and understood.

\textbf{PATHOPHYSIOLOGY OF LIGHTNING INJURY}\textsuperscript{10,12,32,53,56,112,131,132}

\textbf{Electrical Injury Physics Revisited}

Kouwenhoven determined six factors that affect the type and severity of injury encountered with electrical accidents: frequency, duration of exposure, voltage, amperage, resistance of the tissues, and pathway of the current. However, several inconsistencies appear when these are applied too literally.
Electric field strength, not listed as one of the factors, is at a more useful and accurate concept in explaining and predicting injuries from technical or manmade electricity than the classical Kouwenhoven factors that have traditionally been cited in the medical literature. Figure 3-13 shows 20 kV applied to a 1.8 m (6-foot) man, causing current to ground. This produces an internal electrical field strength of approximately 10 kV/m. When a child chews on an electric cord and suffers a lip burn, the field strength is approximately the same: 110 V applied to 1 cm of a child’s lip generates a field strength of 11 kV/m. Even though no one would classify the child’s injury as a “high” voltage, it is a high electrical field strength and produces the same tissue destruction in a small localized area, much as would a high-voltage injury. Lee indicates the importance of internal electrical field calculations in describing electroporation damage.\(^{128-133}\)

A similar inconsistency involves the breakdown strength of air (the force needed to cause a spark of electricity to cross a gap), which is roughly 4000 V/cm, or 10,000 V/inch. Most people are familiar with the shock experienced from walking across a carpet in the winter, although few appreciate this phenomenon would be classified as “high-voltage” injury by the 500- to 1000-V criterion used in medical literature.

Thus, terms used in the medical literature to categorize electrical injuries, such as high versus low voltage and entry versus exit in alternating current injuries, as well as the simplistic application of Kouwenhoven’s six factors, do not reflect either medical or engineering reality and are poor predictors of injury.

**Lightning Injury Physics**

It is necessary to distinguish between lightning and generator-produced high-voltage electrical injuries, in that there are significant differences between the mechanisms of injuries and their treatment. Although lightning is an electrical phenomenon and is governed by the laws of physics, it accounts for a unique spectrum of induced signs and symptoms that are best understood relative to specific physical properties of lightning.

**Frequency, Voltage, Amperage, and Resistance**

Lightning is neither a direct nor an alternating current. At best, description, lightning is a unidirectional massive current impulse. The cloud-to-ground impulse results from breakdown of a large electric field between cloud and ground, measured in millions of volts. Once connection is made with the ground, the voltage difference between cloud and ground disappears and a large current flows impulsively in a very short time. The study of massive electrical discharges of such short duration, particularly their effects on the human body, is not well advanced. Lightning is said to be a “current” phenomenon rather than a “voltage” phenomenon. Examining the particular voltage in these equations becomes difficult because the voltage between cloud and ground disappears after lightning attachment, and equations such as Ohm’s law \(V = I \times R\) and power calculation \(P = V \times I\) cannot be accurately applied. Thus, we must resort to alternative formulations of the equations.

The energy dissipated in a given tissue is determined by the current flowing through the tissue and its resistance by:

\[
\text{Energy (heat)} = \text{Current}^2 \times \text{Resistance} \times \text{Time}
\]

where a current flows through a resistance for a time \(T\).

As resistance goes up, so does the heat generated by passage of the same current. In humans when low energy levels are encountered, much of the electric energy may be dissipated by the skin, so that superficial burns are often not accompanied by internal injuries.

Although lightning occasionally creates discrete entry and exit wounds, these are rare. Lightning more commonly causes only superficial streaking burns. The exception to this is when “hot lightning,” or long continuous current, occurs. This is a prolonged stroke lasting up to 0.5 second that delivers a tremendous amount of energy, capable of exploding trees, setting fires, and acting like high-voltage electricity to produce injuries. Other factors not understood may contribute to the formation of deep burns, although deep burns similar to those of high-voltage electrical injuries generally are quite rare with lightning.

**Pathway, Duration of Current, Flashover Effect, and Time**

It takes a finite amount of time for the skin to break down when exposed to heat or energy. Generally, lightning is not around long enough to cause this skin breakdown. Probably a large portion travels along the outside of the skin as “flashover.” There is some experimental evidence that a portion of the current may enter the cranial orifices—eyes, ears, nose, and mouth.\(^{126,127}\) This pathway would help explain the myriad eye and ear symptoms that have been reported with lightning injury.

Andrews’ further examined the functional consequences of lightning on the cardiorespiratory function and concluded that entry of current into cranial orifices leads to passage of current directly to the brainstem. In a sheep study, he was able to demonstrate specific damage to neurons at the floor of the fourth ventricle in the location of the medullary respiratory control centers. It is postulated that current travels from the caudal via cerebrospinal fluid (CSF) and blood vessel pathways to impinge directly on the myocardium. Andrews also showed histologic damage to the myocardium, consistent with a number of autopsy reports of inferior myocardial necrosis.\(^{9}\)

An alternative hypothesis can be tested with mathematical modeling.\(^{122}\) Certain assumptions are made in any model, usually based on principles accepted in the literature.\(^{123,124}\) Figure 3-14A shows a model for skin resistance, and its connection to the internal body milieu is shown in Figure 3-14B. Note that the internal body structures are regarded as purely resistive, whereas the skin contains significant elements of capacitance.\(^{9,131}\)

In the model, the sequence of events during the strike starts with the postulate that the stroke attached initially to the head of the victim. From our knowledge now, it seems that this is an uncommon point of attachment, but the model is still useful in illustrating lightning energy flow. For a small fraction of time, current flowed internally as the skin capacitance elements became charged. At a voltage taken as 5 kV, the skin was assumed to break down. (A lightning strike is modeled as a current wave, building to a maximum value in around 8 msec, although this may be “modulated lightning,” that is, lightning that has passed through other structures, such as wiring. Others have measured the rise time of direct lightning as 1.2 to 1.5 msec.) Once the internal current increased, the voltage across the body to earth built up, and external flashover across the body occurred when the field reached the breakdown strength of air.
Figure 3-13. A, If 20 kV is applied to a 6-foot (1.8-m) man source to ground, an electric field strength of approximately 10 kV/m is produced. B, When a child chews on the end of an extension cord, the applied voltage of 110 volts across 1 cm produces an electric field strength of 11 kV/m—higher than the classic "high-voltage" injury. C, This explains the deep full-thickness burns the child receives which one would not predict given the "low-voltage" source.
The results of mathematical modeling of these events are shown in Figure 3-15, and the relative magnitudes of the various voltage components can be seen with their time scale. On this time scale, the times to breakdown are short and most events occur early in the course of the stroke. In summary, in this model, lightning applies a current to the human body. This current initially is transmitted internally, following which skin breaks down. Ultimately, external flashover occurs. Andrews’ draws support for this model from measurements made in the experimental application of lightning impulses to sheep. Further modeling of step voltage injury verified that, for the erect human, this mechanism is less dangerous than is a direct strike.21

Experimental evidence suggests that “a fast flashover appreciably diminishes the energy dissipation within the body and results in survival.” In addition, Ishikawa obtained experimental results with rabbits similar to the human data found by Cooper’s study.22 Cooper23–29 has carried her studies to animals in developing an animal model of lightning injury and has successfully shown primary cardiac arrhythmias, prolonged ventilatory arrest, secondary cardiac arrest, keratogenic skin changes, and temporary lower extremity paralysis.

As current flashes over the outside of the body, it may vaporize moisture on the skin and blast apart clothes and shoes, leaving the victim nearly naked, as noted by Hegner30 in 1917:

The clothing may not be affected in any way. It may be stripped or burned in part or entirely shredded to ribbons. Either warp or woof may be destroyed leaving the outer garments and the skin intact. . . . Metallic objects in or on the clothing are bent, broken, more or less fused or not affected. The shoes most constantly show the effects of the current. People are usually standing when struck, the current then enters or leaves the body through the feet. The shoes, especially when dry or only partially damp, interpose a substance of increased resistance. One or both shoes may be affected. They may be gently removed, or violently thrown many feet, be punctured or have a large hole torn in any part, shredded, split, reduced to lint or disappear entirely. The soles may disappear with or without the heels. Any of the foregoing may occur and the person not injured or only slightly shocked.

The amount of damage to clothing or to the surface of the body is not an index to the severity of injuries sustained within
Figure 3-15. Model of human body adapted for the circumstance of direct lightning strike. Responses of the body model are shown for cases of direct strike with and without subsequent flashover.

a human. Either may be disproportionately great or small. However, in unwitnessed situations, Cooper and others have found that forensic evidence of damage to shoes and clothing may be the most important and reliable indicator in determining whether lightning caused a person’s death.\(^{16,196}\)

The factor that seems most important in distinguishing lightning from high-voltage electrical injuries is the duration of exposure to the current, both because lightning is not around long enough to cause tissue breakdown in the classic burn sense and because of the results of the mathematical modeling describing the path of the energy and how long it is in contact with the body.

**Behavior of Current in Tissue**

High- or low-voltage electric current may be carried through tissue in a direct conduction fashion, obeying simple linear equations such as Ohm’s law. The result is heating of tissues under Joule’s law, with thermally induced cellular death and dysfunction. Simple passage of current may interfere with neural and muscular function.\(^{191}\)
Chapter 3: Lightning Injuries

Earlier in the previous century, electrical injury was thought to occur not only because of thermal effects but also because of some mysterious cellular effects. Unfortunately, the technology was not available to investigate these effects and this idea was largely forgotten. In the last few years, the theory of electroporation has been examined. Cell wall integrity, enzyme reactions, protein shape and structure, and cell membrane "gates" and pumps all operate by changes on the order of microvolts. It is not beyond the realm of imagination that passage of an electric current too small to produce significant thermal damage may cause irreversible changes in these functions, leading to cell death or dysfunction. Induction of electric charges by external electromagnetic fields has been shown to force water molecules into cell walls, causing the occurrence of fatal "poles."

Magnetic Field Effects

It has been stated that some effects of lightning might be magnetically mediated. A case cited in support of this contention was of a golfer under a tree in the company of three other persons. It was stated that death occurred without evidence of current entering or leaving the index case. On the other hand, one accompanying golfer showed evidence of current traversing that survived. It is stated that there is no evidence of shock may have existed—direct strike, flash, and ground potential—but no evidence of any was seen. It was considered that contact potential was not relevant. In this case, with persons under a tree, it would seem possible to explain deleterious effects without resorting to a magnetic hypothesis, but the hypothesis bears examination, because it is a recurrent question.

In the case under consideration, the stroke was considered as a line current 1 m (3.3 feet) distant from the victim, and calculation of peak fields and their effects were given.

In considering the contention, it is useful to consider the stroke as a single line current as referenced; however, one must also gain a feeling for how far from a victim such a stroke will act. If the stroke is close to a victim, then attachment to the victim takes place and electrical effects apply as described earlier. If further away, the magnetic field is operative without attachment and magnetic effects need to be examined. Ground potential at this 1-m (3.3-foot) distance also exists.

It is necessary to find the minimum distance away from a victim that a stroke can reach ground without attachment to the victim. This gives the worst case distance from a victim (the worst case being the closest) at which a pure magnetic field acts without attachment.

The standard striking distance formula gives such a distance. The formula is:

\[ d_e = 10^{0.65} \]

where \( d_e \) (m) is the striking distance and I is the stroke current in kA. This represents the distance at the last turn of the downward stepped leader, such that if an object lies inside this distance, attachment of the leader to the object will take place.

For illustrative purposes, let a stroke have a peak current of 18,000 A (the 50th percentile) so that \( d_e \) is 65.3 m. Pure magnetic effects are applicable at this distance and beyond. Inside this distance, the victim will be subject to electrical current effects. By comparison, the ground potential between two points 1 m (3.3 feet) apart at 60 m (197 feet) from a stroke of 18 kA is about 60 V, assuming earth resistivity of 100 ohm-meters.

In examining the magnetic fields involved at this distance, assume an 18 kA stroke at a distance of 65 m (213 feet) from an individual. The peak magnetic B field (the "magnetic induction" formally quantifying the force on a moving charge in its influence) is:

\[ B_{peak} = \frac{\mu_0 I_{peak}}{2\pi d_e} \]

At 65 m (213 feet), the peak B field is 88 \( \mu T \).

For comparison, the earth's magnetic field is about 1\( \mu T \), and the magnetic fields causing concern for powerline fields are in the 1 to 100 \( \mu T \) range. The magnetic fields used in magnetic resonance imaging (MRI) scanning are around 2,000,000 to 5,000,000 times these levels. Powerline fields are, however, held to be dangerous only if chronic. If one is concerned about a lightning stroke magnetic field, he or she should be entirely concerned about MRI fields. This concern is not seen in practice. Certainly, the time-varying nature of any B field is important, both in terms of the rate of change of the field and of movement of a conductor within this field. If one assumes that the above B field is generated in about 2 \( \mu s \), then the time rate of change for the B field is about 22 T/\( \mu s \). Andrews applied this field to a model head and found an entirely noninjurious current resulting.

It is concluded that magnetic field danger in normal circumstances does not seem to exist. Certainly special circumstances might exist, such as the presence of a pacemaker or the presence of an arrhythmic pathway, but in normal terms, magnetic effects would not seem to be clinically significant during occurrences of lightning strike.

Estimates of Streamer Currents

A fifth mechanism of current impingement on an individual has been recently proposed. This mechanism recognizes that as a stepped leader steps toward the earth from a cloud, an upward leader will emanate from several objects that are possible points of attachment. Of these, a return stroke will evolve perhaps from only one. Alternatively stated, there will be several upward leaders that dissipate without attachment.

The current needed to establish and maintain any upward leader nonetheless must be supplied from the earth, and if a person is the source of an upward leader, current must flow through the person as a first approximation.

Estimating the magnitude of this current is fraught with difficulty because so little is known about upward streamer characteristics. To gain a ballpark estimation of the current, however, the initial resistance of the body might be taken as 1000 ohms, with capacitances being initially uncharged. Minimal investigations have been made, however, to estimate that upward streamer current would seem to be around 200 A. The initial head-foot voltage would therefore seem to be 200 kV, yet flashover is not seen at this stage. This may be explained by the decrease (time constant approximately 2 ms) of head-foot voltage as capacitances become charged, whence it may be well decreased to around 20 kV if upward streamer current decreases to a minimum. Clearly, more information on streamer behavior is needed. The field giving rise to the streamer is therefore in the range 100 to 1000 V/cm, which is below the breakdown threshold in air.
The contribution of air conduction may be estimated from the conductance of air, approximately 120 micro siemens/cm², and the field values stated. These give an air current density of 12 to 120 mA/cm². This represents only a small value compared with body current.

The speed with which a stepped leader makes its traverse is around $5 \times 10^3$ m/s, with a large statistical variation, implying that for a 5-km (3.1-mile) distance, the traverse takes about 10 msec. The time course of current for an upward leader is not known, although it is likely to be less than 10% of this (i.e., 1 msec).

A rough estimate of the exposure of a body to current can be up to 200 A for 1 msec. Time/duration curves indicate that current is in a range where effects are noticed, but there is not a risk for cardiac arrest. While this supports the contention of the fifth mechanism, the major thrust of the argument is that much more study of the parameters of upward leaders is needed.

**INJURIES FROM LIGHTNING**

**Severity of Injury**

Some of the most common signs and symptoms are listed in Box 3-3. For prognostic purposes, victims generally can be placed in one of three groups.

**Minor Injury**

These victims are awake and may report dysesthesia in the affected extremity from a lightning splash or, in more serious strokes, a feeling of having been hit on the head or having been in an explosion. They may or may not have perceived lightning or thunder. They often suffer confusion, amnesia, temporary deafness or blindness, or temporary unconsciousness at the scene. They seldom demonstrate cutaneous burns or paralysis but may complain of confusion and amnesia lasting from hours to days. Paresthesias, muscle pain, and headaches may last for days to months. Victims may suffer tympanic membrane rupture from the explosive force of the lightning shockwave. Vital signs are usually stable, although occasionally victims demonstrate transient mild hypertension. Recovery is usually gradual and may or may not be complete. Permanent neurocognitive damage may occur. Some victims may suffer post-traumatic stress disorder.

**Moderate Injury**

Moderately injured victims may be disoriented, combative, or comatose. They frequently exhibit motor paralysis, particularly of the lower extremities, with mottled skin and diminished or absent pulses. Nonpalpable peripheral pulses may indicate arterial spasm and sympathethic instability, which should be differentiated from hypotension. If true hypotension occurs and persists, the victim should be scrutinized for fractures and other signs of blunt injury. Spinal shock from cervical or other spinal fractures, although rare with lightning, may also account for hypotension.

Occasionally, victims have suffered temporary cardiopulmonary standstill, although it is seldom documented. Spontaneous recovery of the pulse is attributed to the heart's inherent automaticity. However, respiratory arrest that often occurs with lightning injury may be prolonged and lead to secondary cardiac arrest from hypoxia or some other yet-to-be-elucidated cause. Seizures may also occur.

First and second degree burns not prominent on admission may evolve over the first several hours. Rarely, third degree burns may occur. Tympanic membrane rupture should be anticipated and, along with hemotympanum, may indicate a basilar skull fracture.

Whereas the clinical condition often improves within the first few hours, victims are prone to have permanent sequelae, such as sleep disorders, irritability, difficulty with fine psychomotor function and attention, paresthesias, generalized weakness, sympathetic nervous system dysfunction, and sometimes post-traumatic stress syndrome. A few cases of atrophic spinal paralysis have been reported.

**Severe Injury**

Victims with severe injury may be in cardiac arrest with either ventricular standstill or fibrillation when first examined. Cardiac resuscitation may not be successful if the victim has suffered a prolonged period of cardiac and central nervous system (CNS) ischemia. Direct brain damage may occur from the lightning stroke or blast effect (Fig. 3-16). Tympanic membrane rupture with hemotympanum and CSF otorrhea is common in this group.

The prognosis is usually poor in the severely injured group, complicated by any delay in initiating cardiopulmonary resuscitation with resultant anoxic injury to the brain and other organ systems. There are anecdotal reports of successful resuscitation of these victims with automatic external defibrillators (AEDs).

**Differences between Injuries from High-Voltage Electricity and Lightning**

There are marked differences in injuries caused by high-voltage electric accidents and lightning (Table 3-4). Lightning contact with the body is almost instantaneous, often leading to flashover. Exposure to high-voltage generated electricity tends
TABLE 3-4. Lightning Injuries Compared with High Voltage Electrical Injuries

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lightning</th>
<th>High voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy level</td>
<td>30 million volts, 50,000 A</td>
<td>Usually much lower</td>
</tr>
<tr>
<td>Time of exposure</td>
<td>Brief, instantaneous</td>
<td>Prolonged</td>
</tr>
<tr>
<td>Pathway</td>
<td>Flashover, orifice</td>
<td>Deep, internal</td>
</tr>
<tr>
<td>Burns</td>
<td>Superficial, minor</td>
<td>Deep, major injury</td>
</tr>
<tr>
<td>Cardiac</td>
<td>Primary and secondary arrest, asystole</td>
<td>Fibrillation</td>
</tr>
<tr>
<td>Renal</td>
<td>Rare myoglobinuria or hemoglobinuria</td>
<td>Myoglobinuric renal failure common</td>
</tr>
<tr>
<td>Fasciotomy</td>
<td>Rarely if ever necessary</td>
<td>Common, early, and extensive Falls, being thrown</td>
</tr>
<tr>
<td>Blunt injury</td>
<td>Explosive thunder effect</td>
<td></td>
</tr>
</tbody>
</table>

Cardiopulmonary Arrest

The most common cause of death in a lightning victim is cardiopulmonary arrest. In fact, a victim is highly unlikely ($P < .0001$) to die unless cardiopulmonary arrest is suffered as an immediate effect of the strike. In the past, nearly 75% of persons who suffered cardiopulmonary arrest from lightning injuries died, many because cardiopulmonary resuscitation was not attempted.

Primary and secondary cardiac arrests had previously been hypothesized and confirmed with animal studies. Injury first occurs with immediate asystolic cardiac arrest and respiratory standstill. Because of the heart's automaticity, contractions generally resume within a short time. Unfortunately, respiratory arrest caused by paralysis of the medullary respiratory center may last far longer than cardiac arrest. Unless the victim receives immediate ventilatory assistance, attendant hypoxia may induce arrhythmias and secondary cardiac arrest. Alternatively, the respiratory arrest and secondary cardiac arrest may be from more severe injury and not cause and effect.

The course has been verified experimentally in sheep, with initial asystole followed by resumption of a short run of bradycardia, then tachycardia, followed by an eventual atrioventricular block or bradycardia, and finally with second asystolic arrest. Prolonged respiratory arrest has also been confirmed in hairless rats.

It is unknown whether cardiac arrest and arrhythmias induced by lightning are a result of damage to central cardiac and respiratory centers in the brain, to the carotid body and other pacemakers along the cardiac control paths, to feedback control mechanisms within the autonomic nervous center, to the heart, or to a combination of these. Certainly, clinical evidence of general damage to autonomic nervous system regulation has been well documented. Recently, cardiac effects from autonomic nervous system damage have been confirmed in the animal laboratory.

Both asystole and ventricular fibrillation have been reported with lightning strike. As noted in the animal work, asystole seems to be both the first and last response to the strike, as the secondary agonal arrest rhythm of ventricular fibrillation deteriorates. Premature ventricular contractions, ventricular tachycardia, and atrial fibrillation have been reported.

It is not uncommon to find electrocardiographic (ECG) ST changes consistent with ischemia and damage in subepicardial, posterior, inferior, or anterior patterns. Creatine phosphokinase MB-isoenzyme elevation has been reported. The first report of troponin level elevations and cellular damage in a lightning survivor was published by a high-altitude pulmonary physiologist who suffered injury while climbing in the Alps, using himself as a control.

Changes on an ECG may not occur until the second day, making the initial ECG a poor screening tool for ischemia. Several authors stress that cardiac symptoms may not be apparent on initial presentation. Premature ventricular contractions were reported in one patient nearly 1 week after presentation. Whereas most ECG changes resolve within a few days, some may persist for months.

The QT interval may be prolonged following lightning strike and may have implications for the cessation of metabolism hypothesis if torsades de pointes is involved.

Some authors have theorized that vascular spasm is a cause of cardiac damage. However, ECG changes are not always consistent with cardiac vascular supply patterns. Areas of focal cardiac necrosis have been reported in autopsies, and histologic changes have been shown in sheep hearts.

Pulmonary edema may accompany severe cardiac damage. Pulmonary contusion, with severe hemoptysis and pulmonary hemorrhage, may result from blunt injury or direct lung damage.
Neurologic Injuries
Although cardiac arrest may be the only immediate cause of death, lightning injury is primarily a neurologic insult with damage possible to central, peripheral, and sympathetic nervous systems. Injury to the nervous system far and away causes the greatest number of long-term problems to survivors. Tools commonly used in evaluation and treatment include functional scans, such as single photon emission computed tomography, (often positive), positron emission tomography; anatomic scans, such as computed tomography (CT) and MRI (usually negative); neurophysiologic assessment; cognitive retraining; rehabilitation; and psychotherapy. Electroencephalography is often mentioned in other literature, but it is seldom helpful.21,27

Central Nervous System Injury
Gross structural changes to the brain, such as coagulation of brain substance, formation of epidural and subdural hematomas, paralysis of the respiratory center, and intraventricular hemorrhage, have been reported but are all rare and may be more from blunt trauma than from electrical injury. Autopsy findings include meningeal and parenchymal blood extravasation, petechiae, dural tears, scalp hematomas, and skull fractures.35 While MRI or CT may show diffuse edema, intracranial hemorrhage, or other injury, they are more commonly normal.38,41,42 There have been reports of MRI findings in a few acutely injured victims.41

In animals, direct cellular damage to the respiratory center beneath the fourth ventricle, as well as the anterior surface of the brainstem, has been shown.1 Lightning energy has been theorized to enter through the orifices of the head, pass through the area of the pituitary and hypothalamus, and through the CSF into the retropharyngeal area, so that signs and symptoms of endocrine dysfunction, respiratory or cardiac arrest, and sleep disturbances could be reasonably expected and do, in fact, occur.

Seizures may accompany initial cardiopulmonary arrest as a result of hypoxia or intracranial damage.

Electroencephalographs may show epileptogenic foci in the acute phase. These patterns may be focal or diffuse, varying with the site and type of injury. However, most patients do not experience seizures during hospitalization. Some victims, however, including children, develop delayed seizures, some of which present as “absence spells,” memory losses, or blackouts that are often diagnosed as “pseudoseizures.”

Obviously, the victim of prolonged cardiopulmonary arrest may have anoxic brain injury that is not specific to lightning injury.

In Cooper’s study2 of severely injured victims, nearly two thirds had some degree of lower extremity paralysis (keraunoparalysis), usually demarcating around the waist or pelvis, and about one third of victims had upper extremity paralysis.21 The affected extremities appear cold, clammy, mottled, insensitive, and pulseless.11 This is probably the result of sympathetic instability and intense vascular spasm, similar in appearance to Raynaud’s phenomenon. It usually clears after several hours.12,25 Fasciortomies are seldom indicated for lightning injuries, because any signs of compartment syndrome or distal ischemia usually clear with patient observation. Pulses can sometimes be elicited with a Doppler examination. Atrophic spinal paralysis has been reported, as have persistent paresis, paresthesias, incoordination, delayed and acute cerebellar ataxia, hemiplegia, aphasia, quadriplegia (immediate or delayed), and one report of progressive muscle atrophy of the upper extremities.

Nearly 72% of the victims in Cooper’s study suffered loss of consciousness.2 Nearly three fourths of these also suffered a cardiopulmonary arrest.21 Those with cranial burns were two to three times more likely to suffer immediate cardiopulmonary arrest and had a three to four times greater probability of death.21 Persons who are stunned or lose consciousness without cardiopulmonary arrest are highly unlikely to die,21 although they may still suffer serious sequelae.

Whether or not victims have suffered loss of consciousness, they almost universally demonstrate anterograde amnesia and confusion, which may last for several days. Retrograde amnesia is less common. While the victim may carry on a conversation and remember his or her actions before the strike, he or she is often unable to assimilate new experiences for several days, even when there is no external evidence of lightning burns on the head or neck.

Survivors may have persistent sleep disturbances, difficulty with fine mental and motor functions, dysesthesias, headaches, mood abnormalities, emotional lability, storm phobias, decreased exercise tolerance, and posttraumatic stress disorder.63,101

The basal ganglia and cerebellum may be affected.41,42 This agrees with older reports of localization. CNS damage may also eventually present as parkinsonism, extrapyramidal syndrome, or other involuntary movement disorders or signs of intracranial hematoma and hemorrhage, infarction, hypoxia, edema, cerebellar signs of infarction, dysfunction and atrophy, and centrally derived pain and psychological syndromes.30

Peripheral Nerve Injury
The peripheral nervous system may be affected. Pain and paresthesias are prominent features of the injury, particularly in the line of the current passage. It would seem that the majority of ongoing pain and dysfunction may be accounted for in the peripheral nervous system.

Symptoms may be delayed by weeks to months. Paresthesias are frequently seen, often mirroring the area of keraunoparalysis. There is also evidence of autonomic neuropathy.

Autonomic Dystrophy
Chronic pain syndromes may occur. Autonomic dystrophy, also called sympathetic dystrophy or sympathetically mediated pain syndrome, may occur. Such chronic pain syndromes are now subsumed under the classification of the complex regional pain syndromes, which are of types I (previously causalgia) or II (reflex sympathetic dystrophy).

The complex regional pain syndromes are long-term neurologic sequelae that may be caused by even minor injuries to nerves, and are characterized by pain, edema, autonomic dysfunction, trophic changes, including atrophy secondary to disuse from pain, and movement disorder.160,178

Post-traumatic Headache
Many victims of lightning injury exhibit severe, unrelenting headaches for the first several months after lightning injury. Cooper has found acupuncture to be effective for at least some of the headaches. Many victims complain of nausea and unexpected, frequent vomiting spells early in their recovery period.
Dizziness and tinnitus are also common complaints, especially with telephone-transmitted lightning strikes.63,19,25,64,65

**Burns**

Most people assume that, because of the tremendous energy discharge involved, a lightning victim will be flash-cooked.24,25 Fortunately, the flashover effect saves most victims from suffering more than minor burns. Although extensive third and fourth degree burns may occur in combination with skeletal disruption, these are quite rare. Often there are no burns, especially with ground current effects. Another factor is the incredibly short period of exposure, which may also explain the lack of significant burn injury in most cases.

As shown in mathematical models, a portion of the lightning current may travel through the tissues.2 If the electric field in the tissue becomes too large, electrons can be freed from their atoms. Referred to as dielectric breakdown,31 this can cause a large increase in the flow of current and become manifest as an electric arc. This may occur internal or external to the body, the latter when the breakdown strength of air (2 × 10⁶ V/m) is exceeded. Arclike burns can result. This happens more often with high-voltage electrical injury, but may also occasionally occur with lightning.

Cooper has related the prognosis of the victim to the location of the burns.52 Persons who suffer cranial burns are four times more likely to die than those who do not have cranial burns (P < .25). Victims with cranial burns are two and a half times more likely to have a cardiopulmonary arrest than those who do not exhibit burns around the head and neck (P < .025).52 Persons with leg burns are five times more likely to die than those who have no leg burns, perhaps because of a ground current etiology (P < .05).52

Discrete entry and exit points are uncommon with lightning. The burns most commonly seen may be divided into five categories: linear burns; punctate, full-thickness burns; feathering or flowers; thermal burns from ignited clothing or heated metal; and combinations.

Linear burns (Fig. 3-17) often begin at the victim’s head and progress down the chest, where they split and continue down both legs. The burns generally are 1 to 4 cm (1/2 to 1 1/2 inches) wide and tend to follow areas of heavy sweat concentration, such as beneath breasts, down the midchest, and in the midaxillary line.12,25 Linear burns are usually first and second degree burns that may be present initially or develop as late as several hours after the lightning strike. They are probably not primary lightning injuries, but are steam burns secondary to vaporization of sweat or rainwater on the victim’s skin.

Punctate burns (Fig. 3-18) are multiple, closely spaced, and discrete circular burns that individually range from a few millimeters to a centimeter in diameter. They may be full thickness and resemble cigarette burns, but are usually too small to require grafting.

Feathering burns (Fig. 3-19) are pathognomonic of lightning and are known by such names as Lichtenberg’s flowers, filigree burns, arborescent burns, ferning, and keraunographic markings.31,35,51,58,81,100,172,192,197 These markings are not true burns, but usually appear as transient pink to brownish, sometimes lightly palpable, arborescent marks that follow neither the vascular pattern nor the nerve pathways. The pattern found is similar to that on a photographic plate exposed to a strong electric field and has been compared to fractals.100 Sometimes the most superficial skin over the areas will slough or flake off after a few days. Although many pictures exist of these marks, they have never been described histologically. They may represent blood cells forcefully extravasated into the superficial layers of the skin from contracting capillaries. At least experimentally, they follow the current lines seen in flashover in Cooper’s animal model.89,89

On rare occasions, clothing is ignited by lightning, causing severe thermal burns.12,25 A victim wearing metal, such as a necklace or belt buckle, or carrying coins in his or her pocket may suffer second and third degree burns to adjacent skin as the objects become heated by the electric energy.22,113 Fig. 3-20 shows the burn resulting from a metal belt buckle or athletic supporter worn by a young man who was struck while playing softball.

Victims of lightning may exhibit a combination of burns.

**Blunt and Explosive Injuries**

The recipient of a lightning strike may be injured directly from the explosive force of lightning or from a fall (as from a horse or mountain ledge, out of a vehicle, or being hurled by endogenous opisthotonic force). As might be predicted, back and spinal
injuries unrelated to the electrical effects of lightning injury may
occur from these mechanisms. A variety of fractures, including
skull, ribs, extremities, and spine, have been reported in light-
ing victims but are uncommon. Rarely, a burstlike injury of
soft tissue occurs and discloses extensive underlying injuries,
especially in the feet, where boots or socks may explode due to
vapor expansion (Figs. 3-21 and 3-22).

Hemoglobinuria and myoglobinuria are seldom reported.
When they occur, they are usually transient. Myoglobinuric
renal failure has not been reported in the literature, although
one case has been verbally relayed to the first author.

Persistent hypotension should alert the physician to blunt
injuries to the chest, spine, lungs, heart, and intestines that may
lead to complications of prolonged coma, pulmonary con-
tractions, heart failure, and ischemic bowel.

Several victims have complained of jaw pain. A number have
suffered loss of teeth or fillings or necrosis of the jaw and teeth,
and many describe a metallic taste in the mouth for months after
the acute injury. At least one was found to have a styloid process
fracture. Many recovering victims believe that premature arthri-
tis may be a result of their injury.

Eye Injuries*

Ocular injuries may be due to direct thermal or electrical
damage, intense light, and contamination from the shockwave, or com-
binations of these factors.

Although cataracts most commonly develop within the first
few days, they may occur late and are often bilateral. Whereas the cataracts may be the
typical anterior midperipher-
type, posterior subcapsular opacities and vacuolization
seem to occur more often with lightning injuries. Corneal
lesions, hyphema, uveitis, iridocyclitis, vitreous hemorrhage,
choroidal rupture, chorioretinitis, retinal detachment, macular
degeneration, optic atrophy, diplopia, loss of accommodation,
and decreased color sense have also been reported.

References 27, 78–80, 85, 93, 96, 97, 111, 114, 158, 159, 184, 201.
transmitted lightning strikes also may account for otologic damage.3,8,9

Between 30% and 50% of more severely injured lightning victims may have rupture of one or both tympanic membranes from the shockwave effect, concomitant basilar skull fracture, or direct burn damage because of current flow into this orifice.11,32 Otorrhea of the CSF or hemotympanum rarely occur. Disruption of the ossicles and mastoid has been reported. Many cases of permanent deafness are noted in older literature but are seldom found in our time. Facial palsies, both acute and delayed, may occur from direct nerve damage by lightning. Vertigo and tinnitus are common, and nystagmus and ataxia may occur.

Fetal Survival
The fetus of a pregnant woman who has been struck by lightning has an unpredictable prognosis.32 Of 11 cases reported, nearly one half of the pregnancies ended in full-term live births, with no recognizable abnormality in the child. Approximately one fourth resulted in live births with subsequent neonatal death; the remainder were stillbirths or deaths in utero. There has been one report of ruptured uterus after lightning strike.

Hematologic Abnormalities
Several unusual hematologic complications have been attributed to lightning injuries in isolated case reports. These include disseminated intravascular coagulation, transiently positive Coombs’ test, and Di Guglielmo’s syndrome, a type of erythroblastosis characterized by erythroblastopenia, thrombocytopenia, and hepatosplenomegaly. Although there have been anecdotal reports of increased hypersensitivity, development of allergies, and increased risk of cancer in lightning victims, perhaps indicating an immunologic component to lightning injury, these have not been studied.

Endocrine and Sexual Dysfunction
Decreased libido for both men and women and impotence for men are common complaints. Sexual dysfunction may be due to neural, spinal cord, endocrine, autonomic, or neuropsychological injury, drug effects, and possibly other causes, and should not be discounted. A report of male hypersexuality after a lightning strike has not been authenticated but can also be explained from a specific brain injury mechanism. One 32-year-old victim reported amenorrhea and premature menopause as a result of her injury. Others have reported menstrual irregularities lasting for 1 to 2 years.

Psychological and Neurocognitive Dysfunction
It is not uncommon for a person hit by lightning to rest at home for a few days, assuming that he or she is supposed to feel “bad” after being hit by lightning. The victim may not see a physician until family members insist or symptoms do not abate. Neuropsychological deficits may not become apparent until a victim attempts skilled mental functions. Often, the person will attempt to return to work after the injury, but because of decreased work tolerance, short-term memory problems, and difficulty assimilating new information, he or she will be unable to continue in the prestrike occupation.

Although some medical authors were historically suspicious of victims’ complaints of psychological and neurocognitive dysfunction, evaluation of many such patients appears to have confirmed a vast commonality of psychological symptoms. This
should begin to reverse a regrettable tendency, both medically and legally, to discount complaints as evidence of malingering, excessive reaction, conversion reaction, personality problems, or manifestations of “weak” coping strategies.

The syndrome is described first from a clinical viewpoint and then discussed in light of the extant literature.

**Functional Issues**
1. Memory disturbance. Individuals show marked diminution of short-term memory ability. They require shopping lists and reminder lists. Memory for recent names and places is diminished to the point of disability. Individuals tend to self-isolate, stop mixing socially, or avoid going into new circumstances.55,59
2. Concentration disturbance (adult attention deficit disorder). Individuals show deficits in their working memory, are unable to focus attention for more than a short period, and are easily distracted. In particular, reading and understanding are poor. Job training is detrimentally affected. This is worsened by sleep disturbance.
3. Cognitive function. Individuals report diminished mental agility. The keeping of accounts is a noteworthy example. Calculation and estimation become erratic and affect work performance. Ability at mental manipulation and problem solving is markedly decreased.
4. Higher executive functioning. Individuals are neither able to coordinate multiple tasks simultaneously nor able to follow orders for complex tasks they used to perform easily before the injury. One victim described it as if “the office manager of my brain had quit.”

**Behavioral Issues**
1. Emotional lability and aggression. Individuals find that they are more aggressive than before. They are easily frustrated and are liable to have outbursts of temper. The strains on a partnership are significant, and marital and relationship dysfunction is common. An increased state of arousal and anxiety may further complicate distractibility as well as the proper recognition and assimilation of new learning.
2. Sleep disturbance. Extreme fatigue, sleep disturbance, or hypersomnolence is common and may last for years. Flashbacks and nightmares may be experienced.
3. Phobic behavior. Avoidance of the precipitant circumstances is demonstrated, in some cases to phobic proportion tantamount to posttraumatic stress disorder.
4. Depression is almost always present in classic biologic form and should be anticipated. Although the aforementioned symptoms can certainly arise secondary to a depressive state, it would also be reasonable for a victim to react with depression to the decrements in work power and lifestyle engendered by chronic pain, sleep deprivation, or decreased personal performance. A third reasonable possibility is concurrent neuropsychological syndrome and biologic endogenous depression. It is the view of the authors that the psychological disturbance exists as an organic entity and that part of that syndrome is also depressive as a primary organic entity. Both elements “feed” each other, compounding to a mixed picture.

Antidepressant medication may be useful. Formal neuropsychological testing may be used to attempt to validate the injury, quantify a functional baseline, and design cognitive therapy. Very few studies have formally examined the syndrome.166,167,314

Primeau and coworkers point to research difficulties, including sample bias and heterogeneity, methodology (cross-sectional rather than longitudinal or prospective), and the essential difficulties of determining premorbid status or current independent psychiatric status. It is also noted that the magnitude of insult does not correlate with psychological disability.55,59 Duration, type, and severity of the syndrome are therefore unpredictable.

Disturbances of verbal memory, attention, concentration, and new learning are very frequently identified.166,167 This commonality among victims is noteworthy.

Primeau and coworkers also draw attention to the similarity of some facets of the disorder and those of other etiologies. They generally find the head injury model a useful one that can guide treatment. Other syndromes for which the lightning and electrical injury syndrome shows similarities include posttraumatic stress disorder, depression, anxiety, and obsessive and adjustment disorders. Features of these are seen to be present, although the syndrome is not simply an example of these dysfunctions per se.

The authors have considered somatoform disorders as a cause, noting the tendency to be preoccupied with the injury and to overattribute subsequent symptoms to the lightning injury. This may be due, in part, to the general lack of knowledge by physicians of the problems and likely outcomes of the injury, so that victims do not know what to expect in the future.

Conversion reaction may also be considered, although it cannot account for the symptomatology of lightning and electrical disability.59 Good neuropsychological testing can detect this facet. One difficulty with neurocognitive testing is use and interpretation of the Minnesota Multiphasic Personality Inventory, which, although it was not developed to characterize patients with chronic problems, particularly those with chronic pain, has been applied to them, often resulting in erroneous conclusion of conversion reaction or preoccupation with physical complaints. It should be a surprise to no one that anyone suffering from chronic pain and neurologic injury that hampers their normal preinjury activities will rank higher on the “preoccupation with physical complaints” and “conversion” scales than will uninjured normal individuals.

Andrews and coworkers8 recognized three postinjury syndromes and correlated these with the postinjury periods of 1 week, 1 week to 3 months, and 3 months to 3 years. Primeau and coworkers66 add a fourth, which is persons experiencing longer and perhaps lifetime dysfunction.88

The first 12 months after injury are crucial to recovery. It is in this period that the most recovery is seen, with possible mild improvement up to 3 years after injury. Beyond this time, chronic dysfunction may be assumed, although it is also at this time that the survivor may decide to move on with life, accept limitations, and even sometimes be able to successfully pursue a new career.

Van Zomeren and coworkers186 provide one of the few thorough examinations of the syndrome in lightning-injured patients. Fatigue and energy loss were the main complaints; poor concentration, irritability, and emotional lability were other common themes confirmed. Impairment of memory, attention, and visual reaction times were documented. Depression and “convincing signs of posttraumatic stress disorder” were seen. The syndrome was highly differentiable from normal (P < .001), and no parallel model was available for comparison. They stated that the lasting complaints and mild cognitive impairments could not be explained on the basis of anxiety reac-
RECOGNITION AND TREATMENT OF LIGHTNING INJURIES

Diagnosis
Diagnosis of lightning injury may be difficult. History of a thunderstorm, witnesses who can report having seen the strike, and typical physical findings in the victim make diagnosis easier but are not always present. Lightning can strike on a relatively sunny day, thunder may not be appreciated, and sometimes the victim is alone when injured. A diligent historical effort and careful physical examination at the earliest opportunity may help determine the true cause. Cloud-to-ground lightning data for past times and places are available to verify the possibility of thunderstorms. Any person found with linear burns and clothes exploded off should be treated as a victim of lightning strike (Fig. 3-22).

Diagnosis is made doubly difficult as burns, which most people expect to accompany lightning injuries, are often absent. Feathering marks, also called Lichtenberg’s flowers, are pathognomonic of lightning strike and are infrequently encountered. Another sign/symptom complex includes linear or punctate burns, tympanic membrane rupture, confusion, and outdoor location. Because there have been several cases of side flash or contact injury from indoor plumbing and telephones, the physician should suspect lightning strike in persons found confused and unconscious indoors or during a thunderstorm.

Initial First Aid and Triage of Victims
As in any other emergency, the first steps are the ABCs: airway, breathing, and circulation. If the victim has suffered a cardiac arrest, cardiopulmonary resuscitation should be started immediately and a rescue vehicle called for transportation. Automated external defibrillators (AEDs) have been helpful in some cases. If the strike occurs far from civilization and evacuation is improbable, the victim will probably die unless pulse and respirations resume spontaneously in a short period of time. The heart may resume activity but may slip into secondary arrest. It is unknown whether the secondary cardiac arrest is due to primary brain damage, hypoxia from prolonged respiratory arrest, primary cardiac damage, or autonomic nervous system damage. If no pulse is obtained within 20 to 30 minutes of starting resuscitation, it is reasonable to stop further resuscitation efforts. If a pulse is obtained, ventilation should be continued until spontaneous adequate respirations resume, the victim is pronounced dead, continued resuscitation is deemed unfeasible owing to rescuers’ exhaustion, or there is danger to rescuers’ survival.

When lightning strike involves multiple victims, resources and rescuers may not meet the demand and triage must be instituted. Normally the rules of triage in multiple-casualty situations dictate bypassing dead persons for those who are moderately or severely injured and can benefit from resuscitation efforts. However, “resuscitate the dead” is the rule in lightning incidents, because victims who show some return of consciousness or who have spontaneous breathing are already on the way to recovery. The most vigorous attempts at cardiopulmonary resuscitation should be directed to the victims who appear to be dead because they may ultimately recover if properly resuscitated. Survivors should be routinely stabilized and transported to the hospital for more thorough evaluation.

The probability that lightning victims can recover after prolonged cardiopulmonary resuscitation (several hours) is not high. There is no evidence to suggest that survival after a longer period than normal without resuscitation is possible in the setting of lightning injury. If the victim has not regained a pulse after 20 to 30 minutes of resuscitation, the chances of recovery are slim and the rescuer should not feel guilty about stopping resuscitation. Often in a remote setting, the rescuer is emotionally tied to the victim by age and friendship and may tend to continue resuscitation past the point of futility. In pronouncing a victim dead, the rescuer must be sure that other problems, such as hypothermia, are not contributing to the victim’s response to resuscitation efforts.

Other stabilization procedures, including splinting of fractures, airway control or intubation, spinal precautions, and institution of intravenous fluids and oxygen, should be accomplished whenever indicated and feasible before transport.

History and Physical Examination
An eyewitness report is helpful, because victims are often confused and amnesic. The history should include a description of the event and the victim’s behavior following the strike. Like any other trauma victim, the victim must be completely undressed to facilitate examination. Special note should be taken of the vital signs, temperature, and level of consciousness. Because many victims are struck during a thunderstorm, they may be wet and cold. Hypothermia should be anticipated and treated appropriately (see Chapter 5).

The awake patient should be assessed for orientation and short-term memory. A cursory mental status examination of the lightning victim may reveal good ability to carry on a “social conversation” that easily hides deficits in fine neurocognitive skills. It is easier to detect deficits when the victim cannot assimilate information, perseverates, or asks repetitive questions. Continuing confusion or a deteriorating level of consciousness mandates CT or MRI of the head to rule out an intracranial injury.

Examination of the victim’s eyes is essential to establish pupillary reactivity and ocular injury. However, lack of pupillary reaction or pupillary dilatation should not be taken as a sole indicator of death. Tympanic membrane rupture is an important indicator of lightning strike. Oscillometric disruption may be one explanation for a victim’s lack of appropriate response to verbal stimuli.

Although the pulmonary system may be affected by cardiac arrest, pulmonary edema, or adult respiratory distress syndrome, it is uncommon to witness these initially. The cardiovascular examination should include distal pulses in all extremities, appreciation of arrhythmias, and evaluation of cardiac damage, including ECG changes. Cardiac enzyme elevations have rarely been reported with lightning injury.

The victim’s abdominal examination occasionally demonstrates absent bowel sounds, which suggests ileus or indicates acute traumatic injury, such as contusion of the liver, bowel, or spleen. The examiner should document any skin changes. The victim’s skin may show mottling, especially below the waist. Burns are not universally present or may take a period of hours
to evolve. Notation of pulses, color, and movement and sensory examination of the victim’s extremities are important.

The physical findings and mental state of minimally and moderately injured victims tend to change considerably over the first few hours; careful observation and documentation delineate the course so that therapy can be modified if appropriate. The minimally injured victim can almost always be discharged to a responsible person or require only overnight observation, whereas the severely injured person may require intensive care with mechanical ventilation, antiarrhythmic medications, invasive interventions and monitoring techniques.

**Laboratory and X-ray Tests**

Minimum laboratory examination includes urinalysis (including a test for myoglobin on fresh urine). The more severely injured victim may require tests such as complete blood count, electrolytes, blood urea nitrogen, creatinine, serial cardiac enzymes, and troponin. If the victim is to be placed on a ventilator, arterial blood gases will be necessary; if intracranial pressure monitoring is used, serum osmolality may be required.

An ECG is desirable for most lightning victims. While several types of acute arrhythmias have been reported, they are uncommon. Curiously, QT prolongation is an abnormality sometimes associated with lightning injury and requires careful assessment of the ECG. Radiographs and other imaging studies may be obtained, depending on the presentation and history. Cervical spine imaging should be performed if there is evidence of cranial burns, contusions, loss of consciousness, or change in mental status. In an examination unreliables, or if there are other considerations, such as a fall. The victim who is unconscious, confused, or has a deteriorating level of consciousness requires a CT or MRI scan of the brain to identify trauma or ischemic injury. X-ray studies to rule out fractures, dislocations, and other bony injuries are obtained as indicated.

**Treatment**

**Fluid Therapy**

An intravenous line is mandatory for the victim who shows unstable vital signs, unconsciousness, or disorientation. If the victim is hypotensive, fluid resuscitation with normal saline or Ringer’s lactate solution is required, with the caution that cerebral edema may develop. Fluid restriction in normotensive or hypertensive victims is recommended because of this risk.

Arterial or central venous pressure monitoring may be indicated. Careful intake and output measurements are necessary in the severely injured patient and require placement of an indwelling urinary catheter. Myoglobinuria is rare and usually transient, so that mannitol diuresis, alkalization, and aggressive fluid loading used with high-voltage electrical injuries are rarely necessary. However, if burns are severe and extensive, which is rarely the case, fluid resuscitation may be required.

**Fasciotomy**

Intense vascular spasm with lightning usually is caused by sympathetic instability. The presence of keraunoparalysis, paralyzed and pulseless extremities seen with lightning injuries, should not be treated like similar-apparing traumatized extremities caused by high-voltage electrical injury, but should be treated expeditiously. Steady improvement in the motile, cool extremity, with return of pulses in a few hours, is the rule rather than the exception. Fasciotomies are rarely indicated unless the extremity shows no signs of recovery and raised intracompartmental tissue pressures are documented. Only one case necessitating fasciotomy has been reported as of this writing.

**Antibiotics and Tetanus Prophylaxis**

Prophylactic antibiotics are not indicated. Standard therapy should follow culture and identification of pathogens. Exceptions to this rule include open extremity fracture or cranial fracture that violates the dura. Appropriate tetanus prophylaxis is mandatory if burns or lacerations are present.

**Cardiovascular Therapy**

Management of cardiac arrest is standard, including the use of an AED if available. In the victim who is not in cardiac arrest, vasospasm may make peripheral pulses difficult to palpate. Usually, femoral, brachial, or carotid pulses may be appreciated. A Doppler examination may be necessary to locate peripheral pulses and record blood pressure.

If a victim remains hypotensive, fluid resuscitation may be necessary to establish adequate blood pressure and tissue perfusion. Causes of hypotension include major fractures, blood loss from abdominal or chest injuries, spinal shock, cardiogenic shock, and occasionally deep burns similar to high-voltage electrical burns. As soon as an adequate central blood pressure is obtained, fluids should probably be restricted because of the high incidence of cranial injuries and cerebral edema. The victim who is without spontaneous or adequate respirations should be mechanically ventilated until he resumes adequate ventilation, brain death is declared legally, or the physician and family decide appropriately to cease efforts.

Cardiac monitoring and serial isoenzyme and troponin measurements are indicated if there is any sign of cardiac ischemia or arrhythmia or if the victim complains of chest pain. Injury patterns, as well as arrhythmias, have been reported. The indications for antiarrhythmic drugs and pressor agents are the same as for a suspected myocardial infarction.

Transient hypertension may be so short-lived as to require no acute therapy. However, several cases of hypertension have occurred 12 to 72 hours after lightning strike and seemed to respond well to beta-adrenergic blockers and other antihypertensive medications. Use of newer antihypertensive agents with lightning injuries has not been studied.

**Central Nervous System Injury**

Every lightning victim should have a good neurologic examination. If there is a history of loss of consciousness or if the victim exhibits confusion, hospital admission is warranted. The victim with tympanic membrane rupture, cranial burns, or loss of consciousness, or who shows a decreasing level of consciousness, should undergo cervical spine imaging, brain CT, and possibly brain MRI.

Intracranial pressure monitoring may be a useful adjunct in persons with elevated intracranial pressure. Cerebral edema may be managed with mannitol, furosemide, fluid restriction, and other standard therapies. Although hypothermia was reported to contribute to complete recovery in one victim with prolonged cardiac arrest before resuscitation efforts, there is no evidence that this would benefit all victims.

Early seizures are probably due to anoxia. If there is evidence of CNS damage or if seizures continue after adequate oxygenation and perfusion have been restored, standard pharma-
Chapter 3: Lightning Injuries

Lightning burns are generally so superficial that they do not require treatment with topical agents. In the unusual instance of deep injury, topical therapy should be standard. The findings that lightning burns are superficial and do not require active surgical intervention is reinforced by Matthews and coworkers. Their paper provides a useful guide to the remote need for surgical intervention in lightning injury.

Eye Injuries

Visual acuity should be measured and the victim's eyes thoroughly examined. Catacatast are not uncommon. Eye injuries should be treated in standard fashion and may require referral to an ophthalmologist. Dinakaran and coworkers report a case in which cataract can be ascribed to a telephone-transmitted lightning strike. Case reports of successful treatment of optic neuritis with high dose steroids similar to those used with spinal cord injury have been reported, but because there were no controls, it is not known if recovery would have occurred without their use.

Ear Injuries

Loss of hearing mandates otologic evaluation. Simple tympanic membrane rupture is usually handled conservatively with observation until the victim's tissues heal. Sensory neural damage to the auditory nerve resulting in hearing changes, dizziness, and permanent tinnitus and facial nerve palsies are not uncommon. Ossicular disruption or more severe damage may necessitate surgical repair. Otorrhea and hemotympanum suggest basilar skull fracture. Complaints of pain around the angle of the victim's jaw should lead the physician to a search for occult fracture of the styloid process and other musculoskeletal damage. Gordon and coworkers hypothesize that the injury must include components other than blast and consider burns the most likely. The present authors concur and cite the possibility of the cranial orifices being portals of entry for electrical current. Mora-Magana and coworkers provide a review of the otic effects of lightning.

Pregnant Victims

If a pregnant woman is struck, fetal viability should be assessed, including fetal heart tones, ultrasonography to observe fetal activity, and other standard methods.

Other Considerations

Gastric irritation is occasionally seen. A nasogastric tube is appropriate if ileus or hematemesis occurs. An abdominal CT scan may be indicated in comatose patients who remain hypotensive, because intestinal contusions and hemorrhage have been reported. It is common for the survivor to report continuing nausea and other signs of postconcussive syndrome for several weeks to months.

Endocrine dysfunction, perhaps as a result of pituitary or hypothalamic damage, including amenorrhea, impotence, and decreased libido, has occurred in some victims. Spinal cord or sympathetic nervous system injury or postinjury depression as well as side effects of medication used for pain control may also be a cause of impotence, decreased libido, and sexual dysfunction after lightning injury.

Pronouncing the Victim Dead

Dilated pupils should not be taken as a sole sign of brain death in the lightning victim. It is always necessary to exclude other causes of dysfunction and eliminate them before death is
declared. Hypothermia with lightning injury may cloud end-of-life decisions. Charlton\textsuperscript{20} states that lightning injury carries a high survival rate, so persistence in resuscitation should be the norm. His notion seems sensible, but his statement has drawn substantial correspondence. Campbell-Hewson and coworkers,\textsuperscript{21} for example, raise the notion that it is a falsehood to claim that resuscitation after prolonged arrest is more likely with lightning-induced arrest. The authors entirely agree with this and agree that the notion arose from one misreported case. Certainly, if the victim has not regained a pulse after 20 to 30 minutes of resuscitation, it is reasonable to cease cardiopulmonary resuscitation.

\textbf{PRECAUTIONS FOR AVOIDING LIGHTNING INJURY*}

Lightning strike usually involves individuals, and as previously discussed, injuries are also usually individual. Prevention is more important than cure, and guidelines for individual safety practice have been produced (see www.lightningsafety.noaa.gov, for example).

Other dangerous circumstances, however, include the possibility of strikes to areas where large crowds have gathered, for example, at major sporting events. The possibility for multiple injuries exists, not only to the players but also to the observers.

\textbf{Lightning Safety Guidelines}

A multidisciplinary group of internationally recognized lightning experts updated existing lightning safety guidelines in 1998.\textsuperscript{6,56,57} The new guidelines are available at www.uic.edu/labs/lightninginjury and address varying sizes of groups and evacuation times. Most lightning deaths and injuries occur in isolated events affecting only one person. Because 25 million cloud-to-ground flashes strike the United States every year, it is impractical for the NWS to warn of every potentially dangerous lightning event, so the key to safety is individual education and responsibility.\textsuperscript{66,69,135,136}

The exceptions to this approach of personal responsibility are (1) when adults are in charge of groups of children, and (2) situations where responsibility is assumed by organizers and operators of facilities where large crowds are expected such as sporting or entertainment events. For groups of children, adults must assume responsibility and have a plan for evacuation. Struck by Lightning (www.struckbylightning.org), an organization formed to disseminate safety information, seeks to make “When thunder roars, go indoors” as well known a phrase to children as “Stop, drop, and roll” is for fire safety.

Operators of recreation facilities and promoters of large events carry the responsibility to be aware of threatening weather, determine when events should be canceled, and have a plan of action that includes proper warning, shelter guidelines, and all-clear signals.\textsuperscript{157}

Studies of Storm Data\textsuperscript{108} casualties relative to cloud-to-ground flashes from the National Lightning Detection Network have shown many to occur during infrequent lightning. Casualties in Florida occurred before, during, and after the peak lightning activity in a thunderstorm.\textsuperscript{107} Lengyel at the University of Oklahoma found that half of the lightning victims had enough warning of cloud-to-ground lightning near them before being struck so that application of planning and the 30-30 rule would have been beneficial. The rest of the victims were struck with less warning of the imminent threat of lightning, so lightning detection data and other methods of thunderstorm forecasting can be helpful in addition to direct local observations.

\textbf{Lightning Safety Plan}

Make a plan that will identify a series of steps.\textsuperscript{157} The plan should identify safer places to go, who makes the decisions, how far in advance such actions are taken, how long to stay at the safe location, and backup people to make decisions at non-standard times such as weekends.

Before working in the open or going on excursions, be aware of weather forecasts and conditions. If thunderstorms are forecast later in the day for the time and place of interest, pay attention to updated forecasts and weather conditions. Use NOAA weather radio or other weather-specific source of information. Seek a safe location if a severe thunderstorm or tornado warning is issued. Appoint a spotter to watch for lightning and provide appropriate warnings to people. Severe thunderstorm and tornado warnings issued by the NWS identify specific counties and periods of less than an hour when high winds, large hail, and/or tornadoes are expected, but such warnings do not identify the lightning threat at a particular place or time. So, a warning from NOAA weather radio or a similar source should be considered only as a wake-up call to the general threat of thunderstorms. Then, careful visual attention needs to be paid to nearby lightning and thunder.

\textbf{Approaching Thunderstorm}\textsuperscript{108,109,108,146}

As a thunderstorm approaches, use the 30-30 rule.\textsuperscript{106} This rules states that when the time between seeing lightning and hearing the thunder from that flash is 30 seconds or less, people are in danger and should be actively seeking shelter (the first 30 of the 30-30 rule). A longer count should be used by persons who have a long evacuation time, such as those involved in group sports, mountain climbers, the elderly or infirm, hikers, and golfers, as well as those who are responsible for others. A count of 30 seconds indicates that the lightning was 10 km (6 miles) away. There is still some risk of lightning with a count of more than 30 seconds, but this measure covers about 80% of all subsequent cloud-to-ground flashes that occur after a cloud-to-ground flash.\textsuperscript{108,146}

If you are wearing a backpack that protrudes above your head, it increases your height and risk. It may be worthwhile to shed it because you can run faster to a safer place. Otherwise, it is a myth that wearing or carrying metal attracts lightning.

It is not uncommon for a portion of the sky to be blue when lightning hits. At least 10% of all cloud-to-ground lightning strikes occur with no rain at the location of the strike, so people should not delay until the rain sets in. Pay more attention to the lightning than the rain.

\textbf{End of Thunderstorm}\textsuperscript{108,146}

At the end of the storm, do not underestimate the danger of lightning. Outdoor activities should not be resumed until at least 30 minutes (the second 30 in the 30-30 rule) after the last lightning is seen or the last thunder is heard during the day.\textsuperscript{108,146}

At night, flashes may be visible low on the horizon inside tall thunderstorms 80 km (50 miles) or more away. These are not of much concern unless the lightning channel itself is visible to

\textsuperscript{*References 64–66, 101, 104, 106, 120, 150, 157, 173–177, 191, 194, 203.}
the ground. Waiting less than 30 minutes may be appropriate when a limited number of people can very quickly reach a safe place, but the full 30 minutes should be used by persons who have a long evacuation time, such as for the pre-storm stage. This measure offers nearly complete safety from cloud-to-ground lightning. Every year, a number of people are killed while running to their vehicles during a full in the thunderstorm instead of staying in the safety of the mall or grocery store.

**Safer Places Inside**

Only two places are “safe” from lightning: a substantial building and a metal-topped vehicle. A substantial building in this context is a structure where people normally live or work. Such buildings have wiring and plumbing that take a direct strike to the structure and facilitate its pathway to ground, although both structural and equipment damage may be high in the process. Another common entry point into a substantial building occurs when a flash strikes an outside power or telephone pole or tower, sometimes resulting in the current being carried inside the building through the wiring. Conducting paths to be avoided include electrical appliances, plumbing fixtures, and coiled telephones and headsets. As long as a person is not in contact with these conducting paths inside the building, or within several feet of them, this is a safer place from lightning.

In contrast, small buildings, such as golf shelters, rain shelters, bus shelters, car ports, and garages, may actually increase the person’s risk, depending on the size and height of the building, because side flashes can occur to the occupants. Side flashes from nearby trees to buildings are especially dangerous: 76% of side flashes occur when a tree is within 20 meters (66 feet) of a building. Tents offer no protection because there is no path for the current to travel around a person when a flash strikes at or near the tent. Material such as a foam pad inside a tent offers no protection against the intense current traveling across the ground. Tent pole material—e.g., metal versus fiberglass—has no effect on protection.

Vehicles with metal tops provide a safer haven because the current diffuses around the occupants through the metal, creating a Faraday Cage, and usually arcs to ground from the body of the vehicle. Vehicles with a cloth top, such as a convertible, or recreational vehicle with only a roll bar are unsafe. Antennas and other tall portions of a vehicle may be the most frequently struck features. When the current travels around the outside of the vehicle, a person should not be in contact with conducting metal parts along the path, just as a person inside a house should not be in contact with wiring or plumbing. When a car, truck, bus, or van is struck by a flash, a person inside may be injured if the vehicle is damaged, but being inside is greatly preferred to being in the open when the strike occurs. It is a myth that rubber tires provide insulation inside a vehicle; the metal body that generally affords protection.

A small group of people can be protected by using cars and vans around a youth soccer field, for example. Some golf tournaments place rented school buses around courses for lightning protection involving larger numbers of people. But a substantial building is preferable to a vehicle. During an after-school activity near a school, an alternative is to assure access to nearby school buildings where the playing fields are located.

Devenuto has patented two options for lightning safety (Fig. 3-23). Figure 3-23A shows a pyramid made of three telescoping poles, each of which is short enough to fit into a golf bag. Figure 3-23B shows a proposed lightning conduction cage that
could be prospectively built into golf carts, but the inhabitants would have to be trained not to touch any of the down conductors, including putting their arm across the back of the cart.

Unsafe Places Outside

No place outside is safe during lightning. Consider the situation of a group of trees with some open spaces between them. Lightning tends to strike the tallest object, such as a tree. The tree acts as the connection to bring current to the ground. A person near the tree will be in danger because the current tends to travel in several arcs outward across the ground from the trunk. It is unknown where these arcs will travel across the ground; their paths do not appear to be related to tree roots or any other surface or subsurface feature. Trees are also dangerous because lightning can reach the ground through overhanging branches. In addition, lightning can send a side flash outward from a tree trunk.16

Similarly, a person standing in an open space between trees is in danger because, as mentioned earlier, a leader attaches to the tallest object when its lowest tip reaches down to within 27 to 46 m (30 to 50 yards) of the surface of the earth. Seeking a clearing to avoid trees makes a person the tallest object in the clearing and therefore more likely to be struck. Similar approaches apply to poles and other tall objects. For these reasons, it is not possible to identify where lightning will travel in order to avoid it, so that no place outdoors provides safety.

On or near a body of water, a person is often the tallest object, or close to one. Lightning tends to strike a person or the tallest parts of a boat projecting above the surface of the water. Plan ahead to avoid thunderstorms that are expected to occur while swimming or during other water-based activities. Compare how long it will take to reach safety on shore with how long the storm will take to reach you while on or in the water. A large sailboat or powerboat can be protected with lightning rods and grounding equipment attached to a metal keel or understructure (www.marinelightning.com).

Small caves, ditches, and valleys provide no protection from lightning. Sheltering under a small outcropping or overhang may actually increase a person’s risk of injury, because lightning that has hit a hill tends to literally “drip” onto the person with the rain as it arcs over the ground, especially over small jagged prominences and gaps.

There is no easy remedy to prevent people from getting “caught” in a thunderstorm; more often than not, they have ignored lightning safety guidelines and made several bad decisions. Nothing can substitute for taking the proper initial precautions: know the weather, have a lightning safety plan, and follow the plan.

Wilderness1

No action will achieve safety from lightning in the wilderness away from a substantial building or metal-topped vehicle. There are only two general approaches to lightning safety in the true wilderness. These approaches are to avoid the risk in the first place, and the other is to accept the fact that a lightning risk exists. None of the following are known to lower the lightning risk: being inside a tent, sitting on a pad, removing metal objects from a person, or any configuration of the body.

Avoidance refers to taking into account the lightning threat as it exists. For example, there is a very real threat of lightning during the afternoon in summer over high terrain in the western United States. The threat in this case can be avoided by climbing very early in the day before lightning begins over higher terrain, choosing to climb during seasons when lightning is much less frequent, and postponing the climb on a day with thunderstorms in the forecast to another day without the threat of lightning. Lightning safety, like most other safety precautions, may be inconvenient but necessary if injury is to be avoided.

The pressure of a schedule or other factors may be such that a wilderness activity will take place in the presence of a very real lightning threat. Then, a hiker or climber has accepted the personal risk in the same manner as the risks from dangerous animals or other natural hazards. Nothing can be done in the open to be safe from lightning on a mountain top on a summer afternoon where there is more lightning than in surrounding valleys.16 A knowledgeable and careful hiker will no more seek routes and times that are prone to lightning than enter an area with a high risk of avalanches, bears, or hypothermia.

Large Group Safety

Crowd Safety and Protection3

Special factors applying to crowd safety have been discussed briefly and rarely.3,150 Reports of multiple casualties exist,2,119,122,137,143 however, concerted strategies for crowd protection are scant. Gratz discusses crowd and stadium protection strategies in some detail, and rightly points out the competing issues in crowd protection.190 He highlights the need for a proper management strategy. Andrews2 examined the matter from the perspective of large crowds (up to 100,000) at a major event (The Olympic Games, Sydney, 2000) and while Makkisi and Bruckner150 supported these views, they also discussed smaller groups (order of 100s). Both stress the importance of a responsible person having authority over institution of procedures.

There will be a gradation of strategy depending on crowd size. For example, a weekend sporting match with 100 people present may require practices akin to the individual practices above. However, a major event with crowds of 100,000 may require special considerations. Which of the strategies to implement will be a matter of judgment for each circumstance, but the “responsible person” and a preexisting safety plan are common themes to both.

An initial risk assessment is useful. Factors include the keruonic level of the region, and also recent past history of storms and lightning. In the Sydney case, while the probability of strikes could be predicted based on thunderday levels, it was also noted that 11 severe storms had occurred in the area at the relevant time of year in the past 10 years. Thus, the history transcended the more usual analysis. Other factors that affect the risk include time of year, time of day, local terrain, and the presence of structures providing a degree of “natural” protection. For example, the risk on a city street surrounded by skyscrapers is much less than on an open plain in Florida. Consideration of each factor leads to overall risk assessment.

References


Chapter 3: Lightning Injuries

Preliminary Factors in Crowd Protection

A thorough appraisal of the circumstances of each event must be made to identify risk, not only from lightning but also from items other than lightning, for example, the ability to withstand accompanying natural forces other than lightning, such as wind, driving rain, and hail. These are beyond our present scope but are part of a total risk management strategy.

Special guiding principles for lightning protection of a crowd include:

1. Crowd management, as well as the provision of “simple” technical protection from a strike itself. Psychological and behavioral management strategies are equally important in a crowd environment.

2. Any form of Franklin rod placed in a position to protect a venue or a crowd. This generally needs to be aesthetically appealing or invisible to media observation.

Protection of Crowds Compared with Individuals

With a single person, for example, a competitor, or even a small team of competitors, placement in a protected zone may be all that is needed if risk eventuates. When to do so, however, is the important question. Such a person or group has easy and quick mobility, and the protected space requirement is small. The strategy that can be used is similar to that for individual protection.

With a crowd, managing a protection strategy and its implementation is as important as the technical nature of the strategy itself. Crowd behavior, possibly encompassing panic, can be threatening and dangerous. This can impede an orderly safe activation of a strategy, and a stampede could endanger life. Crowd education is therefore important, and information and maps should be provided, with reassuring explanations, both written and verbal, for what is to happen at each stage.

The psychological impetus to continue a high-level competition in the face of risk is high. Convincing an individual or a team to cease playing may be difficult, so authority to do so needs to be clearly identified. The possibility of competitive advantage to one side when compulsorily stopping competition needs to be considered. Authority needs therefore to be firmly vested and impartial.

There are two options for lightning safety in the large crowd context:

1. The first option is to move an entire crowd (evacuate the crowd) to a protected space in the face of risk. This depends on the size of the particular crowd, availability of protected space in close proximity, and sufficient egress pathway for the crowd to move in an orderly fashion. This latter orderliness also necessitates that the procedure be within the competence of marshals and their ability to maintain order. Such evacuation is appropriate for smaller bleacher seats, perhaps with an individual capacity of 500 people. Examination of a particular site may indicate the presence of protected spaces. In some cases this could be an adjacent warehouse or gymnasium. In other cases, it is possible to evacuate a crowd from its spectating position into the zone protected by the (then empty) stand, including underneath it. Examination of any possible side flash or contact potential or earth potential rise is required. For these reasons, ultimately evacuation is not always a preferred option.

2. In the second case, it may not be realistically possible to evacuate a very large crowd, for example those in a stadium with a capacity of tens of thousands and fixed entrances and exits. The option, therefore, is to protect the crowd “in situ.” That requires technical protection so that these crowds are not at risk (statistically) of being struck while remaining in place, with lightning being intercepted by a mechanical installation. This requires the design of protection structures. If this strategy is adopted, then one has to be assured that the stands will withstand any wind or hail that is possible, and to accept that such a crowd might get wet.

Details of the Alternative Strategies

Evacuation

Evacuation is mostly appropriate for smaller “crowds.” Evacuation sites need to be available and signage appropriate. Sturdy buildings, warehouses, and gymnasiums all provide suitable sites. The site needs to be of such a size that the numbers can be accommodated in relative comfort. It is inappropriate, for example, for 500 people to be crushed into a single room. Event organizers may wish to establish a rollout by providing refreshments. Sanitary facilities must exist. The final consideration is that evacuation must be achieved with appropriate haste, given the exit paths from the stands, transit paths to the protected site, and entrance and settling time into the protected domain.

Protection in Situ

Protection in situ is often the most realistic option for many sites, given that crowds may be large, spare building space may not be available for the numbers required, and exit routes are generally easily saturated and become mobility-limiting factors. This tacitly accepts that being wet in a stand is an unfortunate but accepted consequence of storm activity.

In addition, individuals in transit between stadiums and fields need to be considered if multiple venues are involved. This implies that the venues themselves not only require protection, but transit paths also require protection.

When to Protect

A key to an evacuation protocol, and certainly a key to advising players when an event is to be compulsorily paused, is the question of when to activate an evacuation protocol. The following is an action strategy.

1. Infrastructure. It is proposed that there should be a Lightning Location System (LLS) display unit present within a venue if the event is of large enough size to warrant it. It should be manned by persons skilled in its interpretation and with absolute authority to implement the phases of a management protocol as outlined below. Such authority could conceivably be shared between one or two individuals. Activation of a strategy is not a matter for a committee debate, but rather the application of firm principles known in advance.

From the display, the operator is required to obtain the speed and direction of travel of lightning activity. The important parameter is whether, given speed and direction of travel, a given storm will pass within 10km (6.2 miles) of a competition venue. This is applied below.

If the event is not large enough to justify installation of LLS equipment, then the decision-maker may resort to visual observation, public meteorology advice, and websites with real-time weather and lightning information.

2. Principles. All lightning protection should be in place and operative when there is any lightning activity within 10 km (6.2 miles) of a venue. Let us then say that a half hour is the time necessary to activate the protocol before this distance threshold is breached. This time varies, depending on the time required to activate the protocol (i.e., evacuate). Thus, phases of a management protocol are required to lead up to the highest level of alert, this being at the stage when lightning activity crosses the 10-km (6.2-mile) threshold from a venue.

The operator of the LLS observes the developing flashes, cells, and clusters of thunderstorms, and estimates the speed and direction of each to predict if and when they will enter the 10-km (6.2-mile) zone. If this is satisfied, then the half hour (or appropriate time) leadup plan is activated.

The risk of lightning injury depends on distance from lightning activity. In this case, all protection strategies need to be in place when lightning activity reaches 10 km (6.2 miles) from a venue, this being considered the maximum distance at which a lightning strike constitutes a risk. Just when to start implementing the strategy, however, depends on the leadup time required to have the strategy, such as evacuation, in place. The controller’s tasks are therefore:

- To observe areas of lightning and watch their location, travel direction, and speed
- To determine when lightning will cross the 10-km (6.2-mile) threshold. When the lightning is still an hour away, a formal “watching” phase is declared
- To calculate when lightning will cross the 10-km (6.2-mile) threshold and to activate the evacuation strategy
- To be aware when lightning crosses the 10-km (6.2-mile) threshold, and to declare the highest level of activation; all strategies are then in place and active

3. Protocol for Activation of Lightning Risk Management. The action protocol is divided into three phases:

- A yellow phase alert, which is a warning that lightning activity has been detected and may impinge on the event
- An orange phase alert, when it has been determined that the activity is a half hour from crossing the 10-km (6.2-mile) threshold and requires definite action
- A red phase alert, when lightning is an immediate and imminent risk on or inside the 10-km (6.2-mile) threshold

A yellow phase alert is declared when lightning activity is 1 hour away from a venue. An orange phase alert is declared when lightning activity is one half hour away from a venue. Depending on the venue’s requirements, all competitors in competition should cease activity, and evacuation is required.

Patrons in stands protected in situ should be advised to remain in position and to expect rain. Individuals in transit should be advised to complete their transit as soon as possible, and those at cars and buses should be advised not to commence transit, but to remain in their vehicles. Individuals outdoors should be advised to move to safe areas as shown on maps provided for the purpose.

A red phase alert is declared when lightning activity is within 10 km (6.2 miles) of a venue. By this stage, all movements and evacuations, if necessary, should be complete, with the venue now secure from lightning risk.

**Figure 3-24.** Protected zones on a pathway from light poles of varying height. (Redrawn from Crowd protection strategies: Experience from the Sydney Olympic Games, 2000. Presented at International Conference on Lightning and Static Electricity, Blackpool, UK, 2003.)

**Protection in Situ**

The Franklin rod is often the basis of lightning protection schemes. Many existing structures can be turned into such rods with ease without detracting from appearances. Examples are given below. It is emphasized that these are illustrative only, and proper design is needed when these are being implemented.

Figure 3-24 shows a pathway with light poles of a given height. The spacing of these poles may be selected to protect the pathway, depending on the height of the poles and width of the path.

Figure 3-25A shows the “natural” protected zone around a temporary stand that might form an evacuation region if other risks are accepted. Franklin rods (see Figure 3-25B) added along the back of the stand extend this zone, and also add some in situ protection. Useful Franklin rods are formed by flagpoles that have the required “look.” A horizontal wire at a given height above a stand also provides in situ protection (see Figure 3-25C). These can be made all but invisible, especially to media cameras. Alternatively, they can carry banners, lights, or media cameras.

Figure 3-26 shows horizontal wires providing protection to a group of stands. The width of the protective corridor depends on the height of the catenary, and the position of the corridor can be altered as a design parameter for effectiveness.

Figure 3-27 shows a stadium for a field game like baseball, where an existing stand provides some protection, as do lighting pylons. The addition of overhead wires can complete the coverage.

Figure 3-28 shows the main stadium stylishly and shows how open stands at either end of the stadium can be protected by fine wires, which are all but invisible.
The psychological effects of lightning injuries are under active research and still need clarification. The effects are well documented in the literature. Nonetheless, psychiatric and psychological standards (e.g., the Diagnostic & Statistical Manual of Mental Disorders as well as other standard teaching and textbooks) have not yet incorporated the syndrome into their formulations. Specialties move slowly, of course, but this also highlights that victims represent a numerically small group in routine practice, and routine practitioners, specialists in their own discipline though not in keraunomedicine, are rarely aware of the literature in the subject. Consequently, we see established practitioners without the benefit of seeing many of these cases, or familiarity with the literature, struggling for a diagnosis and trying to fit the "new" syndrome into existing categories.

Research Methodology Problems

Cooper\(^1\) has drawn attention to further features of what is not yet known in lightning injury and documents methodology difficulties. She states that without knowledge of the basic physiology, only general symptomatic aftercare can be rendered. It may be more desirable to have specific treatments or even early interventions that might stop or change the course of the injury cascade that is precipitated by the initial injury.

Research on lightning injuries is difficult (Box 3-4). There are no public health regulations that require reporting of lightning injuries, so cases are difficult to collect and survivors are difficult to locate for studies in any systematic fashion.

Although it may be convenient to use such populations as the membership of LSESSI as a study group, people who join support groups differ from those who do not; they represent only a subset of survivors, and they may have systematic biases developed from the services and materials that LSESSI supplies to its members.\(^2\) In addition, limited research can be done with them due to ethical limitations on human research, national
Figure 3-28. Open field—a properly installed network of overhead cables that can double for moveable cameras can also provide adequate protection. (Redrawn from Crowd protection strategies: Experience from the Sydney Olympic Games, 2000. Presented at International Conference on Lightning and Static Electricity, Blackpool, UK, 2003.)
Box 3-4. Research Problems

**HUMAN RESEARCH**
- Recruitment of cases
- Study biases
- Dispersion of subjects
- Cases must be free from
  - Diabetes and other neuropathic illnesses
  - Drug history
  - Psychiatric history
  - Blunt head trauma

**ANIMAL RESEARCH**
- Expensive—both animals and equipment
- Large number of animals for some studies
- Difficult signal processing problems
- Monitoring equipment design
- Shock timing control considerations
- Definition of dose
- Standardization of dose
- Flashover effect

**MOLECULAR BIOLOGY**
- Cell culture, blood levels, and so on.
- Requires specialized techniques
- Bioengineering, collaboration
- Expensive

**Box 3-5. Why Do 90% Survive?**

Lightning characteristics?
- "Type" of lightning
- "Dose" of lightning delivered
- Timing of hit
- Other meteorologic conditions?
- Physical characteristics of those "hit"?
- Where people were/what they were doing?

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Water maze and other behavioral models need a standardized quiet environment, which is not always possible in the cramped quarters of most animal facilities. In survival or cardiac studies, timing of the shock to either target or avoid the "vulnerable period" must be done on a statistically predictive basis, because direct sensing of the specific targeted cardiac cycle would again result in damage to the equipment.

**Areas of Specific Controversy**

**Survival Statistics**
Box 3-5 lists factors concerning the unknown issues as to why 90% of casualties survive. It is possible that characteristics of a lightning strike or possibly the mechanism by which the current impinges on the individual may be different for lightning fatalities. It is possible that timing of the lightning strike may be the important factor, particularly if it hits during a more vulnerable portion of the cardiac cycle. Although it is possible, it is unlikely that the physical characteristics of people differ sufficiently to cause a difference in mortality. It is unknown if the "lightning desperation position" (formerly known as the lightning safety position or the lightning crouch) changes outcome or, for that matter, if any position is useful.

**Remote and Psychological Symptoms**
A further area of active research is the etiologic origin of symptoms not directly in the line of passage of current. This is as much for electrical injuries as for lightning injuries. Neuropsychological testing consistently suggests an organic origin to the deficits. Imaging, imperfect as it is, suggests unspecified organic impairment. Yet the exact nature of the impairment, its relation to functional pathologies, and its origin remain obscure.

Increasing awareness of the role of the spinal cord in nociception and existence of proximally directed neural pathways may provide a fruitful connection. Release of humoral transmitters may play a role. The importance of premorbid personality predisposition is unknown.

It has been noted by some that the neuropsychological constellation bears resemblance to the psychological effects of other syndromes, like head injury and the response to autoimmune disorders. It is possible the symptom complex that is seen represents a "final common pathway" of brain injury due to many etiologies.

Box 3-6 lists other possible factors yet to be verified.

**Technical Matters**
The degree of lightning injury or "dose" may vary considerably with the mechanisms of injury (e.g., direct, splash, contact), few of which have been modeled or quantified. Other technical factors regarding the interaction of a lightning stroke with the
Box 3-6. Possible Injuring Forces

- Blunt trauma—explosive injury
- Structural changes—direct damage
- Pathway of the injury
- Orifice entry
- Flashover—how much goes through versus around
- Neurochemical changes
- ANS effects
- Electrical effects
- Electroporation
- Cellular level mechanical effects
- Cellular level enzymatic effects
- Subcellular organelle damage

Body are poorly known, such as the effect of multiple return strokes. Although flashover is known to occur, the course of energy going through the victims versus around them, and the duration of energy flow initially or with return strokes is unknown. While these factors have been calculated based on engineering assumptions, actual measurements have never been done on research subjects or simulated subjects to test the assumptions.

**Resources**

Because common imaging techniques like CT and MRI are anatomic tests, results are limited by resolution of the equipment. As anatomic tests, they do not show functional deficits in how the brain, heart, nerves, or other structures behave when injured. Although it has been hypothesized that deficits are at a cellular, subcellular, synapse, or enzymatic level, this has not been actually investigated or measured, either clinically or in an experimental model. Lee has corroborated electroporation of muscle cell walls with high-voltage electrical injury, but the physics of such injury are quite different from lightning physics, and certain important symptoms are different as well. Electroporation has not been investigated in the lightning model or investigated in nerve or brain cells that are more affected clinically than is muscle tissue. Our knowledge of very short (sub-millisecond) impulses and their effects on the body is poor, and it is not a priori obvious that results for longer durations (electrical) are immediately transferable to short (lightning) durations.

**CONCLUSION**

Much remains to be done in defining lightning injury and helping those who have been injured. Because no health research funding agency currently recognizes lightning as a risk significant enough to require research funding, it is likely that many of these questions may never be fully examined in a research setting. In the meantime, probably the best answer is to prevent as many injuries as possible and to help those who have been injured the best we can—however empirically that may be.

The references for this chapter can be found on the accompanying DVD-ROM.