ORIGINAL ARTICLE

Lightning injury as a blast injury of skull, brain, and visceral lesions: clinical and experimental evidences

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Abstract. The present study attempts to better understand the mechanism of injuries associated with direct lightning strikes. We reviewed the records of 256 individuals struck by lightning between 1965 and 1999, including 56 people who were killed. Basal skull fracture, intracranial haemorrhage, pulmonary haemorrhage, or solid organ rupture was suspected in three men who died. Generally these lesions have been attributed to current flow or falling after being struck. However, examination of surface injuries sustained suggested that the true cause was concussion secondary to blast injury resulting from vaporization of water on the body surface by a surface flashover spark. To investigate this hypothesis, an experimental model of a lightning strike was created in the rat. Saline-soaked blotting paper was used to simulate wet clothing or skin, and an artificial lightning impulse was applied. The resultant lesions were consistent with our hypothesis that the blast was reinforced by the concussive effect of water vaporization. The concordance between the clinical and experimental evidence argues strongly for blast injury as an important source of morbidity and mortality in lightning strikes. (Keio J Med 50 (4): 257–262, December 2001)

Key words: lightning injury, blast injury, skull fracture, organ haemorrhage, organ rupture

Introduction

According to the White Paper on Police, 440 fatalities and 685 injuries due to lightning strikes have occurred in Japan from 1965 through 1999.¹ Death due to lightning strike is usually the result of circulatory failure secondary to a cardiac arrhythmia. Concomitant injuries of solid organ rupture, pulmonary haemorrhage, skull fracture, and intracranial haemorrhage are commonly attributed to the direct effect of current flow or falling after being struck. However these lesions are not well accounted for by this hypothesis. We reviewed the medical records or postmortem examination records of individuals struck by lightning and hypothesized that blast injury occurs when a surface flashover superheats and vaporizes water on the body surface. The precipi-

tous expansion associated with the transformation of water to steam causes a concussive effect that produces intracavitary injury, such as liver rupture, pulmonary contusion, and intracranial haemorrhage. To test this hypothesis, an experimental model of a lightning strike was created in the rat.

Clinical Study

Materials

We reviewed the medical records or postmortem examination records of 271 individuals who suffered a lightning injury between 1965 and 1999. Of these, 16 individuals came to our hospital including one who died before arrival and underwent autopsy. Including this

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A part of this study was presented in Japanese at the 59th Conference of the Society of Atmospheric Electricity of Japan on July 16, 1998 and at Jerusalem, Israel 10th Congress of the International Society for Burn Injuries on November 4, 1998.

Table 1 Demographics and Clinical Characteristics of Three Men Killed by Lightning

Age	Scene	Sign	Diagnosis	Flashover	Body surface	Rain
20	Surfing	Haemoptysis, HEAM	PH, BF, ICH	(+++)	Sea water	(++)
44	Rice paddy	Haemoperitoneum (paracentesis)	LSR, LTBF (Radiogram)	(++)	Sweaty	(++)
29	Alpine ridge	HEAM, Bleeding (nose and mouth)	BF, ICH, PH	(+++)	Sweaty	(-)

PH: Pulmonary haemorrhage, HEAM: Haemorrhage from external auditory meatus, BF: Basilar fracture, ICH: Intracranial haemorrhage, LSR: Liver or spleen rupture, LTBF: Left temporal bone fracture. Autopsies were not performed.

individual, there were 56 fatalities from which an autopsy was performed in three individuals.

Results

Skull fracture, intracranial haemorrhage, pulmonary haemorrhage, or solid organ rupture were not identified in any patients who undergo autopsy. Among the 53 fatalities who did not undergo autopsy, three men who died upon being struck suffered a surface flashover spark (streamer) along their wet body surface. These men were believed clinically to have sustained a skull fracture, intracranial haemorrhage, pulmonary haemorrhage, or solid organ rupture as a result of the blast injury. The details of these three cases are as follows (Table 1).

Case 1: A 20-year-old man was killed instantly by a direct lightning strike while he was surfing in a thunderstorm. Haemoptysis and haemorrhage from the left external auditory meatus were identified on the photographs taken by the medical examiner (Fig. 1). Also noted were linear ruptures in the victim's wet suit corresponding to linear burns. An autopsy was not performed. However, it is likely that the haemoptysis was caused by pulmonary haemorrhage, and that the blood in the left external auditory meatus represented an intracranial haemorrhage secondary to a basilar skull fracture with tympanic rupture. The linear wet suit ruptures and linear burns were consistent with a surface flashover due to a direct lightning strike.²

Case 2: A 44-year-old man suffered a direct lightning strike and fell while weeding a rice paddy during a thunderstorm. He lost consciousness immediately and was in full cardiopulmonary arrest upon arrival at the hospital. Spontaneous respiration and heart beat were restored after intubation and cardioversion, but the patient remained in a coma, which progressively deepened. The paracentesis of his distended abdomen produced frank blood, consistent with liver or splenic rupture. The patient died 12 hr after the accident, but an autopsy was not performed. Examination of the medical examiner's photographs revealed a torn cap, a linear

Fig. 1 Photographs taken by the medical examiner of a 20-year-old man killed instantly by a direct lightning strike while surfing during a thunderstorm. Haemoptysis and haemorrhage from the left external auditory meatus indicating basilar fracture with tympanic rupture are present (upper panel). Note the linear ruptures of the wet suit and corresponding linear burns due to the surface flashover (lower panel).

burn at the left temporal hairline, and linear rupture of his vinyl rain gear (Fig. 2). These findings are consistent with a surface flashover due to a direct lightning strike.² A small amount of blood in the left external auditory meatus was likely due to tympanic rupture, and a left temporal fracture was identified by radiography.

Case 3: A 29-year-old climber was struck by a direct lightning strike on an alpine ridge prior to a thunderstorm and was killed instantly. He had exerted himself strenuously and was covered in sweat. His clothes were

Fig. 2 Photographs taken by the medical examiner of a 44-year-old farmer struck by lightning while weeding a rice paddy during a thunderstorm. Note the torn cap (upper left panel), the linear burn at the hairline of the temple (upper right panel), the ruptured vinyl rain gear (middle panel), and the distended abdomen (lower panel).

totally disarranged, consistent with surface flashover.² Haemorrhage from the mouth, nostrils and external auditory meatus were observed. These findings suggested that intracranial haemorrhage with tympanic rupture, basilar fracture and pulmonary haemorrhage had occurred. An autopsy was not performed.

The lesions on these three men cannot be explained by current flow or falling after being struck. We suspected that these lesions were the direct result of a blast injury. All three men had wet skin and suffered a surface flashover. In these cases, the force of the blast was enhanced by the vaporization of water on the body surface. Based on these clinical observations, a model of a direct lightning strike was created in the rat.

Experimental Study

Materials and methods

Creating a model of lightning strike: Adult Wistar rats were used in all experiments. The effect of lightning on four types of injury was studied: solid organ rupture, pulmonary haemorrhage, skull fracture, and intra-

cranial haemorrhage. All animals were obtained from a professional dealer in experimental animals and received humane care in accordance with the guidelines of the Welfare Regulatory Committee of the Tokyo Electric Power Company Hospital. Under anaesthesia by intraperitoneal injection of pentobarbital sodium (5 mg per 100 g body weight), the rats were shaved totally. Blood pressure was monitored by a transducer connected to a catheter inserted into the left or right femoral artery (the ungrounded side). A pneumogram was recorded with a pressure transducer connected to a cuff sewn to the back (organ rupture) or the chest (skull fracture, intracranial and pulmonary haemorrhage group). The rats were placed in the standing position by fixing the chin, tail, and legs with nylon sutures or rubber bands.

An experimental model of lightning strike was created using an impulse generator. The generator charged six condensers (1 μ F each), the full amount of energy (3,468 Joules) was delivered in all experiments, and each voltage-current was recorded.

Studying for organ rupture: Ten rats had saline-soaked blotting paper placed on the hypochondrium; the paper was fixed in place with a bandage. The impulse was applied between the throat and a thick copper wire wrapped around the right hind leg. The wire was extended to the lower right abdomen to create the surface flashover spark along the front of the torso. All of the rats died as a result of being shocked. Organ rupture was determined by immediate laparotomy.

Organ rupture in two additional groups was studied using a modification of the organ rupture model. In the first group ($n = 5$), a thinner copper wire (0.1 mm in diameter) was placed between the throat and right hind leg. In the second group ($n = 5$), the copper wire which ran from the throat to the right hind leg was covered and sewn to the skin with a cotton ribbon soaked with 0.9% saline solution. These experiments were used to determine whether organ rupture is caused by current passing through the body or by the reinforced blast of vaporized water. Organ rupture of killed rats was determined by immediate laparotomy.

Studying for pulmonary haemorrhage: Ten rats had blotter paper soaked with 0.9% saline solution placed along the left side of the back of the thorax; the paper was fixed in place with a bandage. An artificial lightning impulse was delivered between the parietal scalp and a thick copper wire wrapped around the left hind leg. The wire was extended to the loin to create a surface flash-over spark along the left side of the posterior thorax. Chest radiographs were taken before and after discharge. All rats were killed by the electrical discharge and were fixed in formalin and decalcified. The thorax

was cut into ten cross-sections for the histologic examination. Five rats were subjected to discharge using the same method, except that saline-soaked blotting paper was not applied, and the rats were killed by the discharge. Findings in the five dry rats were compared to findings in the ten wet rats.

Studying for skull fracture and intracranial haemorrhage: Skull fracture and intracranial haemorrhage were studied in a single group of animals. Ten animals had blotter paper soaked with 0.9% saline solution placed on the scalp and covered with a cloth hood that had holes for both ears and which was sewn to the scalp. Five animals with a dry shaved scalp served as controls. An artificial lightning impulse was applied between the forehead and the hip, and a surface flashover spark (streamer) was observed along the head and back. All of the rats died, and skull radiographs were taken post-mortem. The 15 dead animals were fixed in formalin and decalcified. The head was cut into eight cross-sections for histologic examination. The radiographs and histology of the head of the two groups were compared.

Results

Organ rupture

Nine rats in ten rats with saline-soaked blotting paper experienced a surface flashover along the right hypochondrium and massive intra-abdominal haemorrhage. Five rats developed both shallow and deep lobe hepatic fissures, and two rats each in the remaining four rats had superficial or deep lobe hepatic fissures. The streamer on the last rat developed along the left hypochondrium, directly over the left lobe of the liver, but the liver remained intact. Massive haemorrhage in this rat was due to isolated rupture of the spleen. Hence three rats showed deep organ rupture only without shallow organ rupture, in which a liver rupture as an experimental model illustrated the appearance of the deep lobe hepatic fissures (Fig. 3).

Skin injury caused by the flashover current was superficial and was in the area of the melted copper wire which connected the throat and the right hind leg. The wire increased the flashover current and decreased the current through the body. Two rats survived, and three rats died. None of these rats suffered liver rupture. The blast in the group with saline-soaked cotton ribbon was much more powerful. The blast blew off the ribbons about three meters from the rats. All these rats were killed instantly, and laparotomy revealed a moderate amount of haemorrhage in the abdominal cavity and shallow hepatic fissures. In the organ rupture experiment, two rats with the copper wire only survived and the remaining eighteen rats were killed.

Fig. 3 Experimental model of liver rupture with saline-soaked blotting paper due to lightning. Photograph is a upper abdominal cavity of the laparotomy which illustrates the deep liver lacerations resulting from a blast injury (arrowheads). The upper scale is 5 mm/division.

Pulmonary haemorrhage

Postmortem chest radiographs of the wet rats revealed infiltrates in the left lower lung. Histologic examination demonstrated pulmonary haemorrhage bilaterally, in the left more than the right and more extensively in the lower than the upper lung field (Fig. 4). Alveolar haemorrhage was scant in the five dry rats, and the major findings were lung congestion consistent with sudden death. Ten wet rats and five dry rats died upon being shocked.

Skull fracture and intracranial haemorrhage

Eight of the ten wet rats had gross evidence of a skull fracture and intracranial haemorrhage (Fig. 5). Six of these eight rats had haemorrhage from the external auditory meatus unilaterally or bilaterally. The two other rats also suffered fracture and intracranial haemorrhage, but these could be detected only on histologic examination. None of the five dry rats experienced fracture or haemorrhage. All animals died upon being shocked.

Discussion

Generally little if any correlation exists between organ and skin injury in lightning strikes. Among victims killed by lightning, surface injuries offer little evidence supporting or refuting a blast injury, although the haemorrhage from the bodily orifices strongly suggests vital organ injury. The one factor common to each mortality in our series was evidence of a surface flashover. The present study attempted to develop a model whereby it could be determined whether a causal relationship exists between surface flashover and intracavity organ injury. Our hypothesis was that the spark blast from the

Fig. 4 Photographs illustrating pulmonary haemorrhage resulting from an experimental model of a lightning strike. Upper panel is a photomicrograph of a transverse specimen through the upper thorax in which haemorrhage is more extensive in the left lung than the right. Lower panel is a photomicrograph of the lower thorax in which massive haemorrhage is present in the left lung, but haemorrhage in the right lung is moderate (haematoxylin and eosin, camera lucida photograph).

strike is reinforced by the vaporization of superheated surface water on victims who are struck when their skin is wet.

In one study of 221 victims of lightning strike, skull fracture occurred in 3%, intracranial haemorrhage in 2%, pulmonary injury (pneumonia, contusion, or edema) in 4.5%, and gastrointestinal injuries in 3%.³ Rupture of the liver and spleen was attributed directly to current flux through these organs.⁴ However no case of hepatic

Fig. 5 Photomicrograph of a transverse section through the right external auditory meatus of a rat killed by an experimental model of a lightning strike. Massive haemorrhage in the middle ear and external auditory meatus with tympanic rupture is seen. Several areas of haemorrhage are apparent around the cerebellar edge (arrowheads). Arrows indicate basilar skull fractures (hematoxylin and eosin, $\times 9$).

or splenic rupture due to a lightning strike has been reported in the last 35 years.

Forty-five autopsies of people killed by lightning were performed between April 1956 and November 1994.⁵ Skull fracture was noted in one person and intracranial haemorrhage in five patients.⁵ That report attributed these lesions to a fall resulting from loss of consciousness or as a direct effect of lightning strike. However, this conclusion is inconsistent with the clinical data in the present report, and at least one other investigator attributed a subdural haematoma to a blast injury rather than to a fall.⁶ Pulmonary contusion was not observed in a series of 45 autopsies.⁵ However, a 68-year-old man who suffered a direct lightning strike during a thunderstorm had a left lower pulmonary haemorrhage confirmed by bronchoscopy.⁷ Haemorrhage was attributed to blunt chest trauma, electrical burn of the tracheobronchial tree, and blast inhalation. However, photographs of this man clearly show disrupted clothes along the left side of his back and burns consistent with a surface flashover in this area.² We contend that the pulmonary haemorrhage represented a blast injury caused by vaporization of water on the man's wet clothes. In another case, a lightning bolt

struck very near to a boy who developed transient patchy pulmonary consolidations bilaterally. These radiologic findings were attributed to the blast injury from the lightning strike.⁸ Two boys in that study who suffered surface flashover developed pulmonary densities on chest radiographs. However neither boy's skin was wet at the time of the accident, so it is difficult to say definitively these contusions were due to a blast injury, as opposed to another form of trauma, such as falling.

Experiments

A concussive blast injury can be created by rapid expansion of steam produced from superheated water. We believed that containment of the water vapor by clothing, or some other external cover, reinforces the concussive effect of the blast. The question was what were the relative contributions of the reinforced blast, electrical flux in the body, and the electromagnetic field produced by the streamer.

In a previous study of surface flashovers, we showed that the mortality in wet rats was lower than in dry rats.² The fatal threshold was determined by the consumption of electrical energy in the rat's body, which is proportional to the square of the current. We found that the current through the wet rat was lower than through the dry rat.² This data is inconsistent with the hypothesis that lesions are caused by an electric knife effect or Joule heat because more extensive injuries were caused by a lower current. In this experiment, the increased current in the copper wire along the abdominal surface increased the electromagnetic field effect in the abdomen, but the abdominal organs were not ruptured. However, covering the wire with the wet ribbon increased intra-abdominal injuries, supporting the blast injury scenario.

The current density through the body associated with a streamer increases as the distance from the streamer nears. Thus the electromagnetic field effect declines as the distance from the streamer increases. In all the rats with a wet thorax, haemorrhage in the upper lung fields near the streamer was less extensive than in the lower lung fields, which were farther from the streamer. This is contrary to what would be expected if the injury was secondary to the electromagnetic field. Additionally, the fact that the skull fracture lines were not in parallel with the current directions means it was extremely un-

likely that the current itself produced the fracture. Thus the possibility that intracavitary lesions are caused directly by current or an electromagnetic field effect is extremely low. The process of elimination leads us to conclude that blast injury resulting from the vaporization of superheated water along the path of the surface flashover is the proximate cause of intracavitary injury in victims of lightning strikes.

Conclusions

Solid organ rupture, pulmonary and intracranial haemorrhage, and skull fracture were created in a model of a direct lightning strike in rats. These injuries were due to the concussive effect of rapidly expanding steam produced by superheating water on the body surface by a surface flashover (streamer). This mechanism explains common findings in patients who have sustained lightning injuries.

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