Injury Mechanism and Treatment Based on the Impact of Lightning on Personnel Safety

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Abstract Currently, the number of lightning casualties and casualty rates have significantly reduced in developed countries, but there has been no significant reduction in developing countries. On the one hand, this is due to the high frequency of lightning; on the other hand, the vulnerability of people in developing countries is also an influencing factor. Through case analysis and summary, this paper expounds on lightning injury's mechanism and clinical manifestations. It points out that lightning injury is mainly related to heart problems and the impact on the nervous system, rather than burns, which usually cause fewer consequences. Medical treatment needs to pay attention to the order and principles of treatment. Implementing CPR and auxiliary AED is the most effective way to save lives. Attention should be paid to the practical and effective treatment and nursing of lightning stroke sequelae. Finally, combined with the situation of lightning casualties in China, the existing problems are put forward during the process of early treatment, post-hospital treatment, and nursing observation, which provides an objective basis for the cognition of the scientific nature of the lightning injury.

Key words Lightning; Lightning casualties; Casualty mechanism; First aid; Medical treatment

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Lightning has high voltage, large current, high heat, and strong impact. It poses a significant threat to the development of human society and is "one of the ten most serious natural disasters". Casualties caused by lightning are one of the most severe meteorological disasters. According to statistics, 4 176 deaths are caused by lightning yearly, and high mortality areas are mainly concentrated in southern Africa[1].

In developed countries, due to technological development and changes in the structure of workers, as well as the continuous improvement of lightning safety education and medical treatment, the number of deaths caused by lightning in the 20th century has been dramatically reduced[2]. Furthermore, developed countries can provide timely treatment and follow-up professional medical care, and the survival probability after a lightning stroke is nearly 90%[2]. In developing countries, the number of casualties caused by lightning has remained relatively high. The high per capita casualty rate of lightning disasters in these countries is mainly due to the predominance of farming operations and inadequate lightning protection in these densely populated countries' working and living environments. There are also few studies on the percentage of survivors in developing countries. The injuries and pathological phenomena caused by lightning are incredibly complex. In addition to the direct impact of current, it also includes the damage of indirect shock waves, which will cause electrical effect damage at the multi-system level of the body[3]. The Chinese government has dramatically improved the lightning safety measures for houses, workplaces, schools and other buildings. However, lightning is still the third largest meteorological disaster after a rainstorm, flood and meteorological and geological disasters, causing thousands of casualties every year.

In order to improve the level of lightning safety defence and popularize the prevention and treatment of lightning injuries, this paper provides a comprehensive analysis of the injury mechanism, typical cases, clinical manifestations and medical treatment of lightning casualties. It provides a basis for building a complete system, including lightning safety risk warnings, lightning safety education and personal lightning protection measures.

1 Lightning disaster type

From 2009 to 2018, there were 38 594 lightning-related disasters in mainland China, of which 1 904, or 4.93%, caused casualties. The deaths and injuries caused by lightning disasters were 1 789 and 1 552 respectively. Fig. 1 showed annual lightning casualties. The death toll is 1.15 times the number of injuries. The death toll from lightning disasters in Malawi in Africa is 2.8 times that of the injured, while in developed countries like the United States, the ratio of injury to death is 10 ∶ 1. It shows that China's lightning defence work has been improved to a certain extent. However, it still needs to catch up to developed countries and regions[4]. Lightning has the characteristics of high current, high frequency and high voltage, and its impact effects are mainly manifested as electrical effects, thermal effects, mechanical effects, electromagnetic induction, *etc.* Due to the different impact effects, the injury to personnel is also different, so it is essential

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to understand the injury mechanism of lightning[5-7].

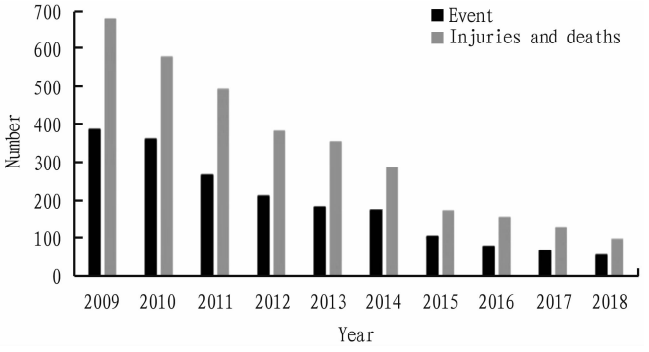

Fig. 1 Distribution of lightning casualties from 2009 to 2018

There are usually six types of lightning damage: step voltage, collateral flashover, contact damage, uplink pilot, direct lightning strike, and blunt trauma. Cooper *et al.* proposed the first five, and Blumenthal gave the sixth mechanism through experiment and analysis based on the original five injury mechanisms[8]. In this paper, the explosion accident of electric detonators triggered by lightning and the secondary casualties caused by the collapse or falling of buildings and structures by lightning are classified into the sixth category. This injury mechanism is usually mass death and mass injury.

Affected by the differences in the quality of data collection of lightning casualties across China, it is impossible to count the types of lightning casualties and injuries across China. This paper takes the types of lightning injuries in Guangdong Province as an example. Guangdong Province is one of the provinces with the most severe lightning disasters in China. The permanent resident population of Guangdong Province ranks first in China, the number of thunderstorm accidents also ranks second in China, the GDP ranks first in China continuously, and there are many ways of production and life, which is representative of China. According to the statistics of 772 lightning casualties in Guangdong Province from 1995 to 2018, the most common form of injury is a direct lightning strike, accounting for 65%, and the second largest injury is a side flashover, accounting for 26%. In addition, it was found that 3.4% of blunt trauma is caused by lightning stroke (Fig. 2). This result is different from Cooper's statistics that only 3% – 5% of direct lightning strikes in lightning injury events in many countries and regions. It should be noted that the direct lightning stroke counted in this paper has the judgment of lightning entry injury. The cases of only blackening or clothing burst injury are classified as the impact of step voltage.

2 Mechanisms of lightning injury

The following is an analysis of six common injury mechanisms and typical cases.

2.1 Ground current Ground current, also known as potential ground rise and step voltage. Earth current means lightning strikes the earth's surface and spreads through it, harming nearby people and livestock. It mainly occurs outdoors and in buildings without lightning protection measures, which may cause mass casualties. When the grounding current reaches 40 – 50 V, people will be in danger of electric shock, and their feet will cramp, causing their bodies to fall to the ground, thus increasing the harm of lightning voltage to the human body. It is generally believed that an electric current lasting for 2 s in the human body will cause electric shock or death after a person falls to the ground.

Case 1: on June 26, 2004, 30 villagers in Duqiao Town, Linhai City, Taizhou City, Zhejiang Province, gathered under five big trees to shelter from the rain. Suddenly, they were struck by lightning. 11 people died on the spot, 19 were sent to the hospital for treatment, and four died one after another. There are five trees of different sizes on the site of the lightning strike point, the height of the trees is between 5 and 10 m, and there are no buildings higher than the trees around. The trees are used as lightning arresters. In addition, there is much rain on the ground. Some victims also took umbrellas with metal handles, wore slippers, and stepped in the ponding to form a good lightning channel, and almost every dead person's clothes left traces of being worn by lightning. The injury types of this case include side flashover and step voltage. The injury of personnel only affected by step voltage is relatively mild.

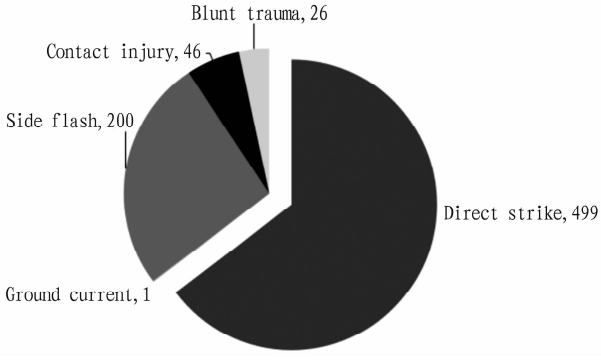

Fig. 2 Types of lightning disaster injuries in Guangdong Province from 2009 to 2018

2.2 Side flash/splash Side flash refers to striking lightning trees and other higher objects. Part of the lightning flows into the ground through objects, and part of the lightning will "jump" to nearby people when passing through the air. If a person is sheltering under a large tree, he or she can suffer this type of injury.

Case 2: at about 15:00 on August 10, 2015, four citizens took shelter from the rain in the pavilion in the scenic spot of the Expo near the convenient service point of the wharf in the east of Haizhu Lake, Haizhu District, Guangzhou, Guangdong Province. One of them was seriously injured.

Case 2 was that before the thunderstorm, when the lightning struck the trees in the open area, it became the main channel of lightning current. Part of the current flows into the earth with the trunk, and the other part breaks through the air and hits the nearby victims. When the current passes through the head, penetrates the chest, and enters the ground through the feet, causing the person to stop breathing and burn marks on the body. The same is true for the primary injury mechanism of case 1.

2.3 Contact injury Contact injury refers to lightning striking

an object and affecting the person who contacts the object remotely through the object. In thunderstorm weather, such injuries will occur when people come into contact with pipes, wired phones or electrical appliances, earphones, or wires of outdoor or internal structures. The voltage generated by lightning is usually tens of thousands of volts, which directly exceeds the critical value of the human body.

Case 3: from 16:00 to 16:30 on May 23, 2007, the classroom of Xingye Village Primary School in Yihe Town, Kaixian County, Chongqing City, suffered a lightning flash many times. When the lightning directly hits the metal window of the classroom, because the metal window is not grounded, there is no place to discharge the lightning current, and the students close to the window become the channel for the lightning flow to the ground. The lightning current's thermal and mechanical effects lead to students casualties. When the lightning strikes the classroom's metal window without a grounding connection, the students near the metal window become the channel for lightning discharge to the ground. The thermal and mechanical effects of lightning currents lead to casualties of students.

2.4 Upward streamer Upward streamer refers to the strong electric field generated in the air during thunderstorm weather. Whenever a thunderstorm passes through an area, objects on the ground near the thunderstorm cloud will generate opposite charges and form tip discharges[9]. It will form an invisible upward guidance channel and try to connect with the downward-moving lightning channel. Even if the last lightning channel is not formed, the upstream streamer still contains enough energy to cause damage.

Case 4: on October 25, 1998, in a football match held in Johannesburg Stadium, South Africa, there was close-range lightning, and six players fell to the ground. Two of them were seriously injured and were sent to the nearest hospital. The CCTV video showed how players were affected by lightning. Evidence suggested that players might be affected by upward streamers, which were emitted from their heads and carried enough current to impact players seriously.

2.5 Direct strike Direct lightning stroke refers to the direct impact of lightning on the human body during a thunderstorm, which occurs in outdoor sports or agricultural labour. Usually, lightning current flows from the top of the head through the human body to the feet and into the earth. There are few clinical records of such injuries abroad, but they account for a high proportion in China.

Case 5: at 16:00 on August 15, 2013, a victim named Qiu, a 24-year-old boy who lived in Mafuxia Village, Wangzhai Town, Wuyi County, Jinhua City, Zhejiang Province, rode home from Wuyitang, Hushan Street after work. When passing through the Tiehoulong section, there was violent thunder over his head, and Qiu fell on the road unconscious.

Case 5 is those thunderstorms. Outdoor workers on their way home suffered direct lightning strikes. Victims are usually characterized by blackening and apparent signs of electrical injury on their heads. Lightning current flows in through the top of the head and flows out from the soles of the feet, and the circuit current flows through the heart, resulting in cardiopulmonary arrest.

2.6 Blunt trauma Blunt injury refers to that when lightning passes through the air, the air is heated and expands rapidly, and the air pressure in the lightning channel immediately rises by 10 or even dozens of atmospheres, and a similar explosion impacts nearby people or livestock. Blumenthal first proposed this lightning damage mechanism, and this damage is equivalent to the impact of a 5 kg of TNT explosion on nearby areas. In addition to the damage to ears and eyes, this shock wave will also cause damage to internal organs such as the spleen, liver, lung, and intestine and even cause secondary damage[10].

3 Lightning injury treatment

The pathological phenomenon caused by lightning injury is highly complex. It is usually an acute injury affected by multiple mechanisms, which will cause different electrical effects on multiple body systems[11]. Therefore, medical rescue is much more complex than other injuries.

Loss of consciousness is the most common, followed by respiratory and cardiac arrest and other organ damage. Early treatment (pre-hospital first aid) is a critical link in the treatment of lightning injury, which can win sufficient time for follow-up treatment to improve the treatment effect and reduce the mortality and disability rate. The first thing to determine when dealing with the scene is whether there is consciousness, breathing and heartbeat. It is necessary to check whether there is a combined injury of the maxillofacial, chest, and abdomen, followed by the electric injury's location, area, and depth. The scene of multiple injuries should be handled according to priorities. The principle is that saving lives is better than saving limbs, and maintaining functions are better than recovering structures.

When the victim of lightning injury has no pulse or cannot breathe normally, cardiopulmonary resuscitation (CPR) should be performed immediately. According to the research, it is the most effective treatment action for lightning victims to carry out CPR for 20 – 30 min in time, although 77% of lightning victims have no response to CPR[12].

At the same time, it is helpful to increase the use of automatic external defibrillators (AED). CPR combined with AED is the most effective rescue method for patients with sudden cardiac arrest and death recognized by the medical community today. According to the research, if AED is used to defibrillate patients within 1 min of cardiac arrest, the survival probability is 90%[13].

Lightning victims suffering from blunt impact injuries should be treated with spinal fixation the first time, and the victims should be transferred to the nearest medical institution for medical observation in time. Victims with persistent musculoskeletal pain, abnormal nerves, heart or blood vessels, or severe burns should enter the intensive care unit as soon as possible.

For lightning victims who show acute transient mild hypertension and tachycardia caused by sympathetic nerve activation, their vital signs are stable and do not need drug treatment. Hypotension after a lightning stroke is a rare clinical manifestation. At this time, the undetected bleeding part of the body should be checked in time. Early seizures may be caused by hypoxia at the moment of

a lightning strike, and the victim's breathing should be improved in time. However, if the victim has recurrent attacks or his mental state deteriorates, it is necessary to rule out brain damage.

In addition to the physical pain from lightning victims, there will be significant psychological trauma simultaneously. On the one hand, neurocognitive and behavioural disorders after a lightning stroke usually lead to failure to return to work and loss of home, and its sequelae also exceeds family members' knowledge and coping ability. Depression, impatience, instant anger, and other personality changes affect the rehabilitation of victims[14]. On the other hand, most lightning victims come from underdeveloped countries and rural areas. It is generally believed that families injured by lightning are "cursed". People around them will avoid the whole family, and the victims can only leave their homes, families, and jobs. Therefore, psychological nursing should be done patiently during systemic treatment.

4 Conclusion and discussion

Based on the case analysis of six lightning damage mechanisms, this paper expounds on the different mechanisms of lightning acting on objects. Clinical manifestations include eight aspects of the impact of lightning on victims and damage. The medical treatment of lightning victims should be prioritized. The principle is that life-saving is better than limb preservation, and maintenance function is better than recovery structure. It is also emphasized that early treatment is crucial. Using CPR and AED well is the most effective rescue method for lightning victims in the early stage. It provides an objective basis for understanding the scientific nature of lightning damage.

The systematic research and attention on lightning stroke injury in China is not enough, which is reflected in the following four aspects. First, most lightning casualties occurred in rural areas where high-quality early treatment and medical treatment could not be obtained. After the injury, active and reliable medical care could not be provided in time. At the same time, the public lacked the awareness and practice of CPR and AED and missed the golden 8-min first aid time for on-site treatment. Especially in the face of lightning group injuries, it was impossible to identify and classify first aid quickly. Many wounded died on the way to the hospital by ambulance. Second, the complexity of the impact of post-hospital treatment on lightning stroke injury is not apparent. Only obvious damages, such as cardiac, respiratory arrest and burn area, are dealt with in time. Survivors who have no apparent symptoms but have a severe visceral injury after a lightning stroke cannot be found and treated in time, resulting in some irreversible injuries, such as aggravation of deafness injury, delay of cataract recovery, and sudden increase of a great deal of myoglobin in the kidney, even dying, *etc.* Third, the mechanism of nursing and rehabilitation measures for lightning stroke survivors' physical and psychological sequelae is not sound enough, and interdisciplinary assistance services are needed, including social, family, and community support. Some developed countries can guarantee rehabilitation support for the sequelae of survivors of natural disasters and provide them with work opportunities within their capabilities. However, China has not yet established a mechanism to pay attention to the individuals and families of lightning-stroke survivors. Fourth, the popularity of lightning stroke injuries in China is insufficient, especially in some rural areas. There are still cases where families or individuals who have been injured by lightning are "cursed" and disliked by people around them. Because lightning stroke is concealed, medical treatment and psychological rehabilitation cannot play a role.

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