Investigating the risk of lightning's pressure blast wave

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DATES:
Received: 05 June 2014
Revised: 17 July 2014
Accepted: 09 Aug. 2014

KEYWORDS:
lightning; flash moisture vaporisation theory; sixth mechanism theory; barotrauma; keraunomedicine; keraunopathology

HOW TO CITE:
Blumenthal R, West NJ. Investigating the risk of lightning's pressure blast wave. S Afr J Sci. 2015;111(3/4), Art. #2014-0187, 5 pages. http://dx.doi.org/10.17159/sajs.2015/20140187

We investigated the pathology of human trauma associated with lightning's pressure blast wave. Within what range is a human at risk and what are the risks? Two theories for the trauma currently exist: the flash moisture vaporisation theory and the sixth mechanism theory. We performed a simple proof-of-concept experiment in a high-voltage laboratory to determine which theory makes for better predictions. The experiment confirmed the existence of a non-discriminant pressure blast wave around a spark in air. The lightning data were compared with the known medical data. Findings may now help explain some of the more curious lightning injury patterns seen on lightning-strike victims.

Introduction and background history

It is well known that injury from lightning is capricious and unpredictable. Clothing may be torn off, which can lead to the suspicion of foul play if the lightning aspect is obscure, or unwitnessed. The clothing is typically ripped open as if by an internal explosion, and belts and boots may be similarly ruptured.[1] Two theories currently exist as to why the clothing of a victim of a lightning strike ruptures, tears and tatters: the flash moisture vaporisation theory and the sixth mechanism theory.

Flash moisture vaporisation theory

Ohashi et al.[2-4], through a process of elimination, came to the conclusion that blast injury results from the explosive vaporisation of superheated water along the path of the surface flashover. To investigate their hypothesis, an experimental model of a lightning strike was created in the adult Wistar rat. Saline-soaked blotting paper was used to simulate wet clothing or skin, and an artificial lightning impulse was injected. The resultant lesions were consistent with their hypothesis that the blast was reinforced by the concussive effect of water vaporisation. 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 thought to be caused by the concussive effect of rapidly expanding steam produced by superheating water on the body surface by a surface flashover (streamer). This mechanism has been proposed to explain some of the common findings in patients who have sustained lightning injuries.

Sixth mechanism theory

The sixth mechanism theory was recently proposed. The sixth mechanism of lightning injury may be thought of as a 'pressure-shock wave' which is directly proportional to the current of the lightning discharge, and which is present immediately surrounding lightning's luminous channel. A laboratory experiment was designed which helped confirm the sixth mechanism's existence. Its existence may also help explain some of the more curious lightning injury patterns seen on lightning-strike victims.[5]

Cooray et al.[6] reported that injuries can be caused by shock waves created by the lightning channel; however, they did not commit to a specific distance within which a victim would be at risk from blast wave injury. During a lightning strike, the channel temperature is raised to about 25 000 K (24 727 °C) in a few microseconds, and as a result, the pressure in the channel may increase to several atmospheres. The shock wave associated with the lightning flash may reach overpressures of 10–20 atmospheres (1013–2027 kPa) in the vicinity of the channel. In addition to causing damage to the ears and eyes, this shock wave may also cause damage to other internal organs such as the spleen, liver, lungs and bowel tract. Moreover, it may suddenly displace the victim from one place to another, causing head and other traumatic injuries.[6]

If flash moisture vaporisation theory were indeed a reality, why are forensic pathologists not reporting scald burns on lightning strike victims? Superheated water would likely cause scald burns on the skin of lightning fatality victims. Forensic pathologists instead report scorch burn wounds on the skin, singeing of hair and torn-and-tattered clothing akin to explosive (blast) barotrauma.[1,7]

Uman et al.[8] published a paper on a shock wave from a 4-m spark. The shock wave emitted by a 4-m spark of energy 2 x 104 J was measured at distances from spark midgap of between 0.34 m and 16.5 m. Close to the spark, a single dominant shock wave was observed; farther from the spark, a number (generally 3 or 4) of significant shock waves was observed. For distances less than 2 m, both the shock overpressure and the duration of the overpressure were a factor of between 1.5 and 5 lower than predicted by cylindrical shock-wave mathematical theory. The discrepancies between the experimental data and cylindrical shock-wave mathematical theory were partially explained by consideration of the spark channel tortuosity.

Plooster[9] studied the cylindrical pressure wave resulting from instantaneous energy release along a line in a quiescent atmosphere by numerical integration of the equations of gas dynamics. An approximate equation for the radial dependence of shock strength, applicable to most of the numerical solutions, was presented. Plooster's experimental measurements of shock strengths from detonation of long explosive charges were shown to be in relatively good agreement with the numerical solutions.

Previously, wires were passed through gels to investigate the nature of the shock wave.[5] What would happen if there were no wire? Would the blast effect simply dissipate on the surface of the skin? There is nothing in the medical literature that suggests that the pressure blast wave of a lightning strike would rip a cavity in human flesh. More rigorous scenarios and analyses are needed. The lightning data with regard to structural risk do not seem to align well with the medical data. It is for this reason that an experiment without a wire path for the current needed to be designed. The experiment also needed to be constructed in such a way as to focus on the real questions: at what range is a human at risk and what is that risk?

Materials and methods

A simple proof-of-concept experiment was created to determine which theory makes for better prediction with regard to lightning explosive barotrauma. Previous experimental set-ups were examined[8-10] and the 'sixth mechanism experiment' was designed (Figure 1).

The experiment was conducted to test for the presence or absence of a blast wave surrounding lightning's luminous channel in air. The testing took place at the University of the Witwatersrand's School of Electrical and Information Engineering High Voltage Laboratory and utilised an 8/20-μs current impulse generator (built in-house at the School of Electrical and Information Engineering's High Voltage Laboratory). The magnitude of the current impulse was measured by means of a Pearson coil (model 301X, Pearson Electronics, Palo Alto, CA, USA) connected to a Rigol DS 1064B digital oscilloscope. An isolation transformer was used to protect the oscilloscope from any surges that may have occurred on the mains supply during the experiments. It must be noted that this wave form does not represent that of natural lightning, which has a longer rise and fall time.

The 8/20-μs waveform is commonly used to simulate induced lightning currents and was thus selected for the purposes of our experiment. These waveforms are indicative of induced currents from a nearby direct strike. The energy is lower (because of the shorter duration) and therefore this waveform seemed suitable for a proof-of-concept approach.

A further consideration with respect to this waveform was that the current waveform of a direct lightning strike is modelled as a 10/350-μs waveform. This means that the rise time (time to get from 10% of peak to 90% of peak) is 10 μs. The fall time (time to reach 50% of the peak value) is 350 μs. A lightning waveform, as a consequence of its long duration, delivers a significant amount of energy, as one would expect from a direct lightning strike. In a laboratory environment, this energy is difficult to manage.

The experiment consisted of discharging high-voltage sparks through a 250 mm x 250 mm piece of dry graph paper, saline-soaked graph paper and distilled water soaked graph paper. Distilled water was chosen for its similarity to rain water and saline was chosen as an alternative to sweat. The peak current versus the maximum diameter of tattering were then plotted on the respective graph papers. All graph papers were tested at generator charging voltages of 15 kV, 18 kV and 20 kV. These voltages equated to peak currents of 24.5 kA, 29.2 kA and 32.5 kA, respectively. Maximum and minimum diameters were then measured with scientific callipers. Finally, an average diameter for the irregular tears was determined using mathematical principles. Because of the fact that risk is determined as distance from lightning's luminous channel, the perimeter length (circumference) of the tear was not measured.

If sixth mechanism theory (meaning a pressure blast wave around lightning's channel) were indeed a reality, all papers – wet and dry, conductive and non-conductive – would show tearing and tattering. If flash moisture vaporisation theory were the reality, only the wet papers would tear and tatter, or there would be more tearing and tattering in the wet papers.

The maximum radial diameters of the tearing and tattering probably would provide the best indication as to the range within which a human would be at risk and what that risk would be.

Preliminary findings are presented here; a more comprehensive data set is required to test the reliability and validity of the results.

Results

Figure 2 and Figure 3, respectively, show the dry and saline-soaked graph papers after they were subjected to an impulse. The majority of knowledge related to lightning parameters has been derived by 'scaling up' the equivalent information obtained during experimentation using long linear electrical discharges generated under laboratory conditions.[8]

The minimum, maximum and average diameters of the resultant tears after dry, distilled water- and saline-soaked graph papers were subjected to increasing impulses are shown in Table 1.

Figure 4 shows the maximum tearing diameters against the peak generated currents for dry, distilled water- and saline-soaked graph papers. Trendlines showed greater tearing of the paper soaked in 0.9% saline than of the dry or distilled water soaked papers. The tearing diameter of the paper soaked in 0.9% saline was higher than those for the dry and water-soaked papers. However, it can be seen that there is not much difference between the maximum tearing diameter for the dry paper and that for the paper soaked in distilled water.

Tearing and tattering occurred in all the papers, confirming the existence of a non-discriminant blast wave around a long, linear spark (lightning's luminous channel).

The greater extent of tattering in the saline-soaked paper could be because of the conductive nature of saline. The saline-soaked paper probably 'held on' to more charge than the other specimens.

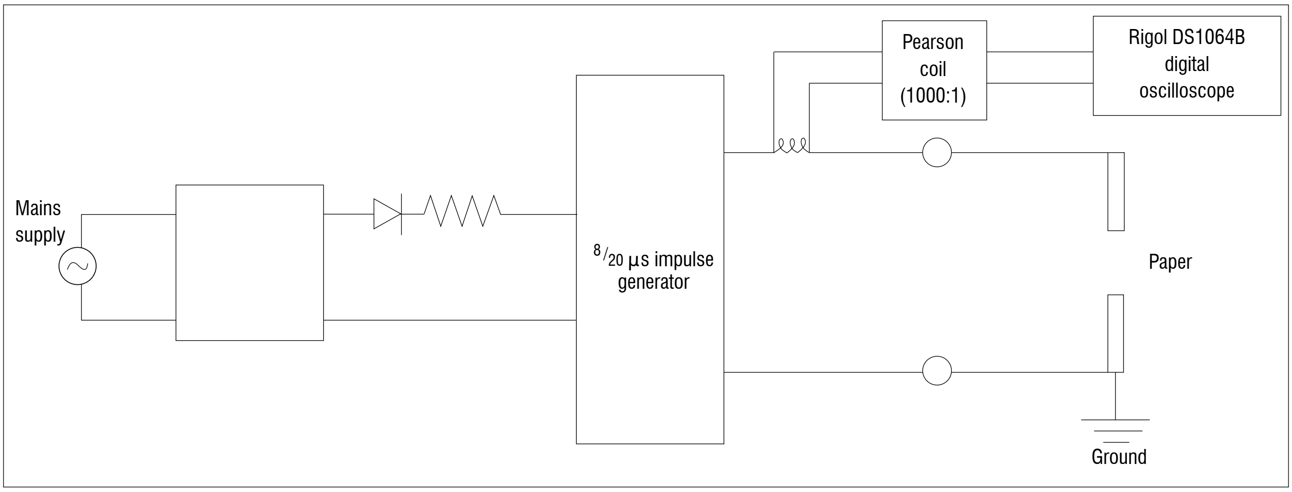


Figure 1: The 'sixth mechanism experiment': Physical layout of the current impulse generator and test object (graph paper).

Discussion

We know that there exists a pressure blast wave around lightning's luminous channel. We have known about it since the time of Gaius Plinius Secundus, better known as Pliny the Elder (23 AD – 79 AD). Pliny the Elder was a Roman author, naturalist and natural philosopher, as well as naval and army commander. His dictum was 'the man who sees the lightning flash and hears the thunder, is not the one to be struck'[11].

One can hear thunder from as far away as 25 km,[12] which means that there is a tremendous amount of energy involved in the generation of thunder. However, before thunder occurs, there is a pressure blast wave. This pressure blast wave is caused by the superheating of the air around the lightning bolt, which travels at supersonic speeds. It is this supersonic blast wave which decays, within metres, and transforms into thunder. Many people think that lightning injuries in humans are chiefly caused by lightning's electricity and heat. While this belief is true for the vast majority of lightning-related deaths and injuries, the accompanying pressure blast wave can also do serious harm.

As mentioned, the temperature of the lightning bolt channel is raised to about 24 727 °C in a few microseconds. This increase causes the temperature around the channel to rise suddenly, resulting in the pressure in the channel suddenly increasing to several atmospheres. Charles's law dictates that the volume of a gas is directly proportional to its temperature, that is, the higher the temperature of a gas, the greater its volume. The combined and ideal gas laws therefore predict pressure changes with temperature changes. This sudden rise in volume causes a sudden cylindrical-shaped pressure shock wave, which may reach pressures of more than 10–20 atmospheres (1013–2027 kPa) in the vicinity of the lightning bolt channel. This energy is enough to form a small crater in a concrete pavement. When a lightning flash makes contact with rocky soil, the electric current tends to follow the interstices between the rocks or cracks. Rocks may be split asunder or even thrown aside with explosive violence.[13] Whether this effect is a result of cracks being filled with moist soil (flash moisture vaporisation theory) or solely a result of the lightning's pressure blast wave (sixth mechanism theory) has been the topic of debate.

Lightning's pressure blast wave has been known to tear and tatter clothing, indirectly fracture long bones, rupture a person's eardrums and damage their lungs. The blast causes a pocket of air behind the sternum (pneumomediastinum)[14] and it may cause injury to the chest wall and lungs[15]. These findings are similar to those one would expect to find in victims of bomb explosions. The force may cause a victim to fall, causing head and other traumas. Lightning strikes have even been known to cause shrapnel injury– one victim had multiple small fragments of shattered concrete pavement embedded in her skin.[16]

The human body is paradoxically both very robust and very fragile. Humans can survive relatively high blast overpressures without experiencing blast-related pathologies.[7] Thus far, blunt force trauma injuries, torn and tattered clothing, fractures, traumatic perforation of tympanic membranes, lung contusion and haemorrhage, and pneumomediastinum, as a result of lightning strikes, have been documented in the medical literature. The aforementioned injuries appear to represent the documented risks, seen in practice, to date.[5]

The findings reported in flash moisture vaporisation theory can all adequately be explained by sixth mechanism theory. The purpose of this paper was to compare the theories and determine which theory provides for better predictions with regard to lightning explosive barotrauma.

A blast consists of a wave of compression passing through the air. The velocity of the shock wave depends on its distance from the epicentre;

Table 1: Minimum, maximum and average diameters (mm) of tears in dry, distilled water- and saline-soaked graph papers after being subjected to different impulses (kA)

Peak current (kA)	Dry paper			Water-soaked paper			Saline-soaked paper		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
24.5	18	29	21	15	20	15	13	18	15
29.2	10	24	15	8	22	10	29	56	18
32.5	13	43	20	25	39	23	40	80	40

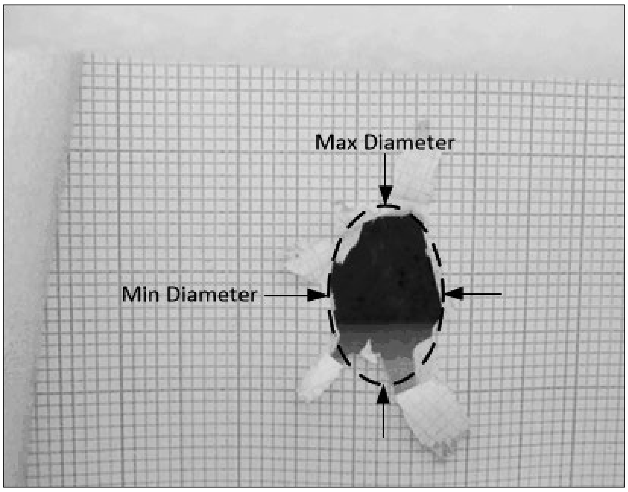


Figure 2: Dry graph paper after being subjected to an impulse of 24.5 kA (generator charging voltage of 15 kV). The maximum and minimum diameters of the tear in the dry graph paper were 29 mm and 18 mm, respectively.

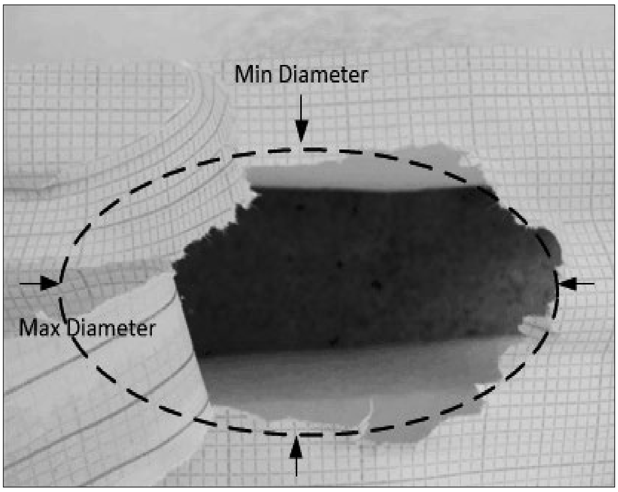
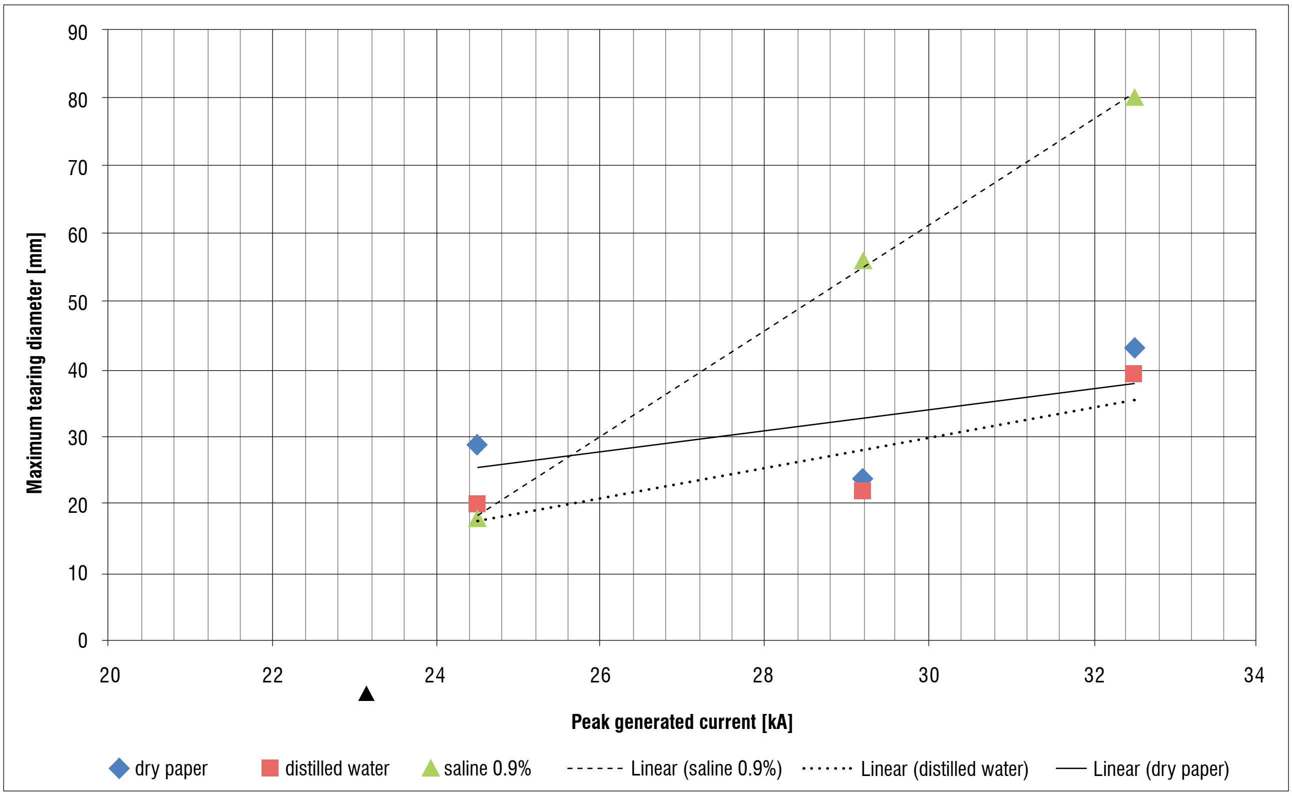


Figure 3: Saline-soaked graph paper after being subjected to an impulse of 32.5 kA (generator charging voltage of 20 kV). The maximum and minimum diameters of the tear in the 0.9%-saline-soaked graph paper were 80 mm and 40 mm, respectively.



Spark gap = 5 mm

Figure 4: Graph demonstrating incremental tearing diameter in dry, distilled water- and saline-soaked papers.

the velocity is many times the speed of sound at the start, but rapidly decreases as the shock wave expands outwards. The magnitude of the blast varies with the energy released and distance from the epicentre; the intensity obeys the inverse square law. An explosion classically gives rise to a narrow wave of very high pressure which expands concentrically from the seat of the explosion at about the speed of sound. The pressure is exceptionally high at the front of the wave but decreases towards its rear and becomes a slight negative pressure, or partial vacuum, before the wave is complete. Such a wave will temporarily engulf a person as it moves through them.[7]

The generation of cylindrical shock waves by the release of energy along a line in a gas has not been as thoroughly studied as the analogous point-source spherical wave problem. Yet there are a number of phenomena, both natural and artificial, which closely resemble line disturbances. Artificial line sources include exploding wires, long explosive charges, electric sparks, and supersonic aircraft or projectiles – lightning discharge being the outstanding natural phenomenon.

Lee[17] combined results from several sources to determine the intensity of the pressure from the stroke current magnitude and the distance from the stroke terminal to a susceptible structure. Hill[18] also looked at peak shock pressures from the lightning stroke channel. Their findings were chiefly aimed at lightning protection of structures and their findings need to be aligned with the medical data.

If one knew the initial conditions (thermodynamics and flow parameters as a function of radius at selected instants of time), one could possibly numerically solve this problem; however, there always are varying initial conditions, for example the magnitude and strength of the lightning discharge.

Depending on what literature one reads, there is also data from weapons tests and blast studies to assess the effect of blast overpressure on structures and people.[19-21] These data provide some guidance on the possible effects of explosions on humans: personnel are typically knocked down by explosive overpressures in air at 7–10 kPa (1.0–1.5 psi); eardrums typically rupture at 35–100 kPa (5.1–14.5 psi); and lung damage is induced at approximately 200–500 kPa (29.0–72.5 psi).

The human body can survive relatively high blast overpressure without experiencing barotrauma. A 34-kPa (5-psi) blast overpressure will rupture eardrums in about 1% of subjects, and a 310-kPa (45-psi) overpressure will cause eardrum rupture in about 99% of all subjects. A study by Richmond et al.[22] suggests a minimum threshold of about 20 kPa (2.9 psi) to produce minor eardrum ruptures.

Theoretically, one could take the aforementioned sixth mechanism laboratory experiment results, together with the known medical literature and the known high-explosive overpressure constants and consequences, and model the risks of natural lightning.

Conclusion

In our laboratory experiment, the diameter of the tear created by a simulated lightning strike was larger in the paper soaked in 0.9% saline than in the dry or water-soaked papers. These findings concur with those of Ohashi et al.[2-4] Despite the difference in size, tearing and tattering occurred in all the papers, suggesting the existence of a non-discriminant blast wave around a long, linear spark (lightning's luminous channel).

The data obtained from our laboratory experiment align relatively well with high-explosive overpressure observations in the field. Sixth mechanism theory would therefore appear to make for better predictions in the field than flash moisture vaporisation theory.

These findings do, however, pose further questions, such as: what parameters, e.g. distance to strike and current level, are necessary to see such blast damage and/or injuries? The answers to these questions are not trivial and the real test will lie in the duplication of these findings in other laboratories, in practical field assessments and in forensic pathology investigations.

Knowledge and insight into lightning's pressure blast wave may have direct and indirect applications to those working in the fields of lightning injury and lightning protection.[23]

Acknowledgements

A special word of thanks to Professor Ian R. Jandrell and his team from the School of Electrical and Information Engineering, University of the Witwatersrand, without whom none of this would have happened.

Authors' contributions

The work presented in this paper extends and contributes to research in the field of lightning injury mechanisms. R.B.'s contribution was the alignment of the medical, forensic and lightning data. N.J.W.'s contribution was the set-up and performance of the sixth mechanism experiments. Both authors contributed towards the analysis of the results.

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