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Keraunoparalysis and burning thatch: A proposed explanation for severe lightning injuries reported in developing countries

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ABSTRACT

It is well known that lightning strikes produce direct and indirect consequences in power utilities and systems, which have been addressed by implementing lightning protection systems. However, dealing with the effects of lightning on people is different due to the complexity of the human body and the multiple mechanisms by which a person can be injured by lightning. While lightning injuries in developed countries seldom show significant burns, those killed by lightning in developing countries are often characterized as 'charred' or 'burned beyond recognition'. Keraunoparalysis, an immediate but temporary paralysis of one or more limbs after lightning injury, occurs in many victims and may be the reason that even healthy individuals cannot escape from burning thatched buildings, explaining these descriptions in news reports. Keraunoparalysis and burning thatch make a deadly recipe.

1. Introduction

In developed countries, most lightning incidents involve single deaths and lightning burns tend to be superficial with less than half of survivors reporting skin damage or burns of any kind [1]. However, news reports in developing countries often describe people with lightning injury as 'burned beyond recognition' or 'charred' [2, 3]. It was unclear why lightning injuries would be different in different countries. One hypothesis was that busy reporters in countries with limited communication who had no contact with the victims or the scene were merely describing what they expected to be the findings in order to meet the deadlines of their editors for a short account [4].

In reflection and over time, the authors have collected reports with pictures showing complete conflagration of thatched roofs and buildings and first-person accounts of hearing victims inside buildings hit by lightning screaming but being prevented from helping them because of the ferocity of the fire [2-5] [Figs. 1 and 2]. It was unclear why inhabitants of the buildings might be screaming but unable to escape until keraunoparalysis ('kerauno' for lightning + paralysis) was considered.

This paper proposes keraunoparalysis that results in being trapped in a flaming thatched structure is one explanation for why descriptions of lightning injuries vary so markedly between developing and developed countries. In this paper 'thatch' serves as a general term for building materials constructed of straw, reeds, palm leaves, or similar material, which is usually highly flammable.

In the developed world, keraunoparalysis usually occurs to people outside and not at risk of fire; therefore, keraunoparalysis is not a consideration inside 'safe' substantial buildings where it is very rare nowadays to see injuries [1]. Even if a building were to catch fire, it is unlikely to burn as rapidly as the generations-old, tinder-dry thatch that is a common part of dwellings in developing countries. It is estimated that 90% of sub-Saharan dwellings are not lightning safe and that entire families are at risk as they live, meet, and sleep within their thatched homes and businesses [6].

The authors report this to the engineering community hoping that this knowledge may influence lightning protection standards, as well as catalyze multidisciplinary studies into keraunoparalysis and other medical effects of lightning injury [7].

2. Methodology

A systematic search in PubMed database, hosted in the US National Library of Medicine (NLM), located at the National Institutes of Health (NIH), was conducted using the term 'keraunoparalysis' in both titles

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and abstracts for the medical and clinical aspects. Because only ten articles were found for the term keraunoparalysis, a more extensive search was based on clinical cases, case series, and keyword references of lightning injuries. Additionally, references from well-recognized texts and other sources were included tempered by the extensive clinical experience of the two physician authors with lightning cases. The engineering literature was searched for relevant modeling of lightning injury, not for clinical aspects.

3. Overview of the term 'Keraunoparalysis'

Today, keraunoparalysis is defined as a transient paralysis suffered after a lightning injury that often includes pulselessness, pallid, mottled, or cyanotic skin, and motor and sensory loss in the extremities [1, 8]. Although keraunoparalysis usually resolves within a few hours without treatment, some survivors have reported lasting weakness [1].

Paralysis is the loss of muscle function, but not necessarily sensation, in one or more parts of the body. It is caused by the interruption of motor signals traveling from the brain to the body part to be moved. Stroke, neurological illnesses, injury, toxins, and other factors may interfere with motor signal transmission and any part of the transmission pathway from the brain to the part to be moved may be involved [9]. Paralysis can affect any part of the body, including one extremity (monoplegia), one side (hemiplegia – arm and leg on the same side), both lower extremities (paraplegia), or all extremities (quadriplegia). Paralysis may have different degrees of severity from partial (incomplete) paralysis and weakness (paresis) to complete paralysis and may be permanent or temporary.

Several authors [10, 11] attribute the term keraunoparalysis to Charcot, a French neurologist, who was said to have coined it in two classic articles published at the end of the 19th century that described the paralysis [12, 13]. However, Cherington [14], a well-known authority on the neurological aspects of lightning and electrical injuries, affirms that the term was not introduced until 1932 by the British neurologist Critchley, a statement ratified by Kumar et al. [15].

The first publication related to lightning injuries registered in PubMed was published in 1800 [16]. In early texts, neurological manifestations from lightning were not documented until 1848 when Orton described a transient paralysis involving weakness and paralysis of the right upper limb with a very slow recovery [17]. In 1883, in a case report describing the first photographic images of Lichtenberg figures, paralysis, weakness, and coldness of both upper limbs were also mentioned without further analysis or information [18].

4. Presentation of the lightning victim with Keraunoparalysis

Cooper's 1980 study was the first organized case series analyzing the signs and symptoms reported in the literature for lightning injury and remains the largest series of lightning injury cases reported to date (66 patients) [19]. It reported loss of consciousness in 72% and confusion or amnesia in 86% of those documented. Paralysis was found in 43.9%, with about 2/3 affecting the legs and 1/3 the arms as summarized in Table 1 [19]. As a review of published cases, it should be recognized that it is biased toward findings that would be publishable, not the people having milder, non-publishable cases, so that these numbers probably do not reflect a true distribution of cases over the entire population of lightning victims. The Lightning Strike and Electric Shock Survivors International support group documents findings reported by its members [20, 21]. Review of the literature documents that paralysis may affect one [22, 23], a combination [15,24–28], or all four extremities [29, 30]. Keraunoparalysis is usually transient, lasting a few minutes to a few hours, although occasionally permanent weakness persists [1]

In the authors' (Cooper and Navarrete) extensive clinical experience, from hearing and reading innumerable accounts, and receiving correspondence from survivors and their families worldwide, many, but not all, lightning survivors report loss of consciousness in the immediate aftermath of the injury. Lightning victims report gaining some consciousness after an unknown length of time post-injury and being able to begin perceiving their surroundings but unable to move one or more extremities to help themselves or others who were injured. Similar clinical findings would be expected regardless of the country of origin. Even young, healthy people who experience these effects would be unable to evacuate a building although their relatively unimpaired respiratory status could allow them to call for help. If they were in a thatched building, it may have been burning for several minutes during the time the survivor was recovering from the impaired mental state that frequently occurs with lightning injury. Together, keraunoparalysis and burning thatch would make a deadly combination.

Fig. 1. Eleven tribal counselors were killed in this thatched meeting structure when it was ignited by lightning in Sierra Nevada, Colombia, 7 Oct 2014. Observers who tried to come to their aid reported they could hear the counselors screaming but were unable to rescue them due to the heat of the fire [3, 5].

After synthesizing this hypothesis, the authors and others who monitor lightning reports around the world began to collect reports of incidents where bystanders report they could hear the lightning victims screaming inside their burning homes but that the fire was burning too furiously to help them. These reports come from Africa, South America, and the Caribbean (Figs 1 and 2) [2, 3, 5, 31].

Keraunoparalysis is accompanied by other clinical findings, including intense constriction of blood vessels causing coldness and pallor of the extremities [1, 8]. It may be difficult for even medical personnel to feel a pulse, leading to misdiagnosis of cardiac arrest so that bystanders may initiate cardio-pulmonary resuscitation (CPR) in a patient who does not technically require it [1, 24, 32]. However, the American Heart Association (AHA) has long recommended that CPR should be started when there is doubt, and it does little harm to those who do not need it besides some bruising and perhaps a broken rib or two. Given the alternative of death if CPR were not started in those who really need it, it is wiser to apply CPR in any case of doubt, as the AHA decided nearly two decades ago [33].

Dilation and absence of pupillary reaction can also be associated with lightning injury and keraunoparalysis [1], leading an observer to conclude that the person is dead. The rule of thumb in both situations is to begin CPR until either the rescuers are exhausted, 20–30 min has passed without a response, or the presence of a cardiac rhythm can be reliably ascertained, at which point, cardiac compressions, if not ventilation, can be stopped, depending on the ventilatory status of the victim. [1, 33]

The autonomic nervous system (ANS) controls many 'automatic' functions of the body such as pulse, breathing, blood pressure, digestion, sweating, sexual arousal, and other involuntary activities. Bradycardia (slow cardiac rhythm) or tachycardia (fast cardiac rhythm), profuse sweating, and arterial hypertension [14, 34] may be found in patients with keraunoparalysis, so it is reasonable that ANS dysfunction or shock has been postulated as a cause of keraunoparalysis [35]. This hypertension is usually transient and can be treated expectantly. Occasionally, persistent hypertension and other autonomic dysfunction has been reported as long-term sequelae (after-effects) [36].

The physical signs that are seen with a lightning survivor with keraunoparalysis can be initially confused with other diagnoses including spinal cord injury, shock from many causes including infection, and arterial blockage to the extremity involved [1]. Barotrauma, a well-known lightning injury mechanism similar to being near an explosion where the person can be thrown a distance, should be expected and spinal precautions taken [1, 37-40]. Other causes of trauma should always be considered, especially if there are no observers or reporters of the event. Since each of these other diagnoses can lead to treatment that is contra-indicated and even harmful to the lightning survivor, it is important for the clinician to differentiate between them [1].

Table 1
Neurological signs and symptoms commonly seen immediately after lightning injury [summarized from 19].

Factor	Percentage of Survivors
Loss of consciousness	72%
Confusion, amnesia	86%
Paralysis	30% Upper Extremities 69% Lower Extremities

5. Medical theories of causation

Lightning produces a multi-organ compromise, affecting mainly the cardiovascular and nervous systems [1, 40]. At the neurological level, lightning can compromise all three components of the nervous system: central nervous system (CNS – brain and spinal cord), peripheral nervous system (PNS – any nerve outside the CNS), and autonomic nervous system (ANS). Keraunoparalysis, according to Cherington's classification [14], belongs to Class I neurological lesions (immediate and transitory), occurring in about one half to two-thirds of reported lightning cases [41, 42], and typically consisting of limb paralysis, sensory symptoms, coolness, pallor, and pulselessness [Table 2].

The study of keraunoparalysis is not an easy issue. While frequently reported by survivors, physical manifestations are transient and, on many occasions, the symptoms and signs have improved or resolved by the time the patient arrives at a medical institution. Multiple theories

Fig. 2. This woman lost many members of her family who were killed as they were sleeping inside this grass thatched rondavel in South Africa after it was hit by lightning.

Table 2
Cherington's classification of neurological symptoms from lightning injury [adapted from 14].

Group	*Characterization*	*Examples*
Group 1	Immediate and transient symptoms	Loss of consciousness, amnesia, confusion, keraunoparalysis, weakness, headache
Group 2	Immediate and prolonged or permanent	Intracranial hemorrhage, cerebral infarction (death of tissue), post hypoxic-ischemic (lack of oxygen usually from decreased blood flow) encephalopathy, cerebellar syndromes, neurocognitive (thought processing) disorders
Group 3	Possible delayed neurologic syndromes	Movement disorders
Group 4	Lightning-linked secondary trauma from falls or blast	Ruptured eardrums, musculoskeletal damage consistent with falls or being thrown a distance

have been proposed to explain this phenomenon [Table 3]. It has been hypothesized to be from vascular circulatory compromise of the injured limb [43], or to a differential effect according to the route of the discharge [44, 45].

In 1934, Critchley proposed that sensory and neurological symptoms may be related to vasoconstriction (contraction/constriction of the blood vessels) caused by a "massive autonomic stimulation," similar to that in Raynaud's phenomenon, a syndrome where smaller arteries, usually in the fingers and toes, narrow in response to cold or stress making the hands and toes painful and white or blanched – the cause of Raynaud's is not known but it can be primary or secondary to another illness or injury [35, 46, 47]. The current explanation considers a high discharge of adrenaline and other catecholamines (hormones produced by the adrenal glands) as the cause of vasoconstriction [11, 48]. However, the following two questions arise, which could be investigated in the future:

1) if the weakness, numbness, and paralysis are directly related to vasoconstriction, why do neurological symptoms occur in the absence of vascular compromise [24, 25, 49]?
2) if the phenomenon is produced by the effect of circulating catecholamines throughout the body, why don't the vascular and neurological findings occur in all 4 limbs?

It may be possible that several mechanisms act simultaneously that, together, are capable of producing different manifestations in each limb of the same patient [36, 50].

6. Mathematical modeling and investigation of lightning injury

Many have attempted modeling the electrical effects of lightning to the body. These papers can be divided into several categories:

1 Nonspecific, often computational, and applied to electromagnetic fields and current distribution across the entire body [51-53]
2 Investigation, usually computational, of specific mechanisms of injury such as ground current or upward leader [54-57]
3 Computational or experimental models, some involving tissue parameters, but none involving actual animal tissue or physiological or cellular experiments and instrumentation [58-62]. While one moved beyond these to look specifically at the distribution of current density to the skull and brain, it did not address keraunoparalysis or other brain injuries often seen after lightning or the other long-term effects [63].
4 Multidisciplinary studies, often involving engineering, physics, and lightning detection as well as clinical investigation of lightning cases [64, 65]

Table 3
Theories on the causation of Keraunoparalysis.

Factor	*Corroboration*
Vascular spasm	Plausible – but from what cause? [46]
Autonomic nervous system dysfunction	Other autonomic effects should be seen – hypertension, fast or slow pulse, etc. [35, 46, 47].
Catecholamine release (adrenaline, etc.)	Effect would be generalized, not limited to specific limbs [11, 48]
Lightning pathway	Nearly impossible to test or document
Release of other chemicals or hormones?	Andrews hypothesis [36]

Unfortunately, others have made the error of grouping high voltage injuries and lightning together in the study, a mistake frequently made by clinicians who are not familiar with either the physics or the clinical manifestations of the two distinct injuries [1, 66].

While many of these papers were well constructed, they add little that is useful to actionable or practical clinical knowledge of the injury to tissues and humans. There is a huge need to meld the engineering and clinical worlds if either is to understand these injuries more fully and to eventually, perhaps, formulate better care. Fine (as opposed to gross) modeling, corroborated by both observed and experimental tissue injury, of technical, man-made electrical and lightning injuries such as burns, keraunoparalysis and other lightning effects is much needed [20].

7. Conclusions

News reports in developing countries often describe people with lightning injury as 'burned beyond recognition' or 'charred' while it is well known that only about a third of survivors in developed countries report burns, the majority of which are usually superficial and minor in most cases. This paper introduces the deadly combination of keraunoparalysis and burning thatch or other housing materials as a likely cause of the differences between victim reports in developed vs developing countries.

While frequently reported by survivors, keraunoparalysis has had little study, perhaps because of its often-transitory nature. Given this lack of information, the authors strongly encourage laboratory studies with a multidisciplinary collaboration including medicine, bioengineering, physics, and even social disciplines, among others, to clarify this and other pathologies related to lightning injury.

Contributions of each author

All three authors have been intimately involved throughout this paper and its revisions. Specific contributions include:

D.E. Villamil – presented the paper at SIPDA 2019, prepared initial submission to EPSR, searched modeling and engineering literature.

N. Navarrete – searched medical literature and wrote the initial extensive medical review manuscript. The authors decided that there was great value to modify for SIPDA and for publication in the engineering literature. Dr. Navarrete is proceeding with the considerably more detailed medical review article that will be submitted to the medical literature at a later date.

M. A. Cooper – modified Dr. Navarrete's initial draft for SIPDA, reformatted per 'Instructions to Authors,' added modeling literature, and managed revision and substantial reorganization of the paper after first EPSR review as recommended by Dr. Rubinstein.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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