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# PERCEIVED ELECTRICAL INJURY: MISLEADING SYMPTOMOLOGY DUE TO MULTISENSORY STIMULI

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**☐ Abstract—Background: An electrical accident victim's recollection is often distorted by Bayesian inference in multisensory integration. For example, hearing the sound and seeing the bright flash of an electrical arc can create the false impression that someone had experienced an electrical shock. These subjects will often present to an emergency department seeking either treatment or reassurance. Case Reports: We present seven cases in which the subjects were startled by an electrical shock (real or perceived) and injury was reported. Calculations of the current and path were used to allocate causality between the shock and a history of chronic disease or previous trauma. In all seven cases, our analysis suggests that no current was passed through the body. Why Should an Emergency Physician Be Aware of This?: Symptomology seen as corroborating may actually be confounding. Witness and survivor descriptions of electrical shocks are fraught with subjectivity and misunderstanding. Available current is usually irrelevant and overemphasized, such as stress on a 100-ampere welding source, which is orders of magnitude beyond lethal limits. History can also be biased for a number of reasons. Bayesian inference in multisensory perception can lead to a subject sincerely believing they had experienced an electrical shock. Determination of the current pathway and calculations of the amplitude and duration of the shock can be critical for understanding the limits and potential causation of electrical injury.** 

**☐ Keywords—electrical injury; electrical shock; Bayesian inference; low-voltage**

MWK, PEP, and CJA have been expert witnesses in electrical injury litigation. MWK was an expert witness in cases 1, 4, and 6. No other conflicts are reported.

## INTRODUCTION

About 20,000 patients present annually to U.S. emergency departments complaining of an electrical shock, and the majority are low-voltage injuries that typically leave no obvious signs (1). The emergency physician is often challenged to find any sign of injury, yet does not want to incorrectly provide mere reassurance. The patient history typically seems consistent with a true electrical shock.

### *Bayesian Inference in Multisensory Perception*

An electrical injury victim's recollection is often significantly inconsistent with the actual electrical current passed through the body. For example, hearing the sound and seeing the flash of an electrical arc can create the sincere but false perception of an electrical shock. There are many forms of such multisensory confusions. This observation does not imply malintent. Especially when

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flashes, explosions, and noise are involved, victims will report what they think should have happened, and firmly convince themselves that it did happen. The same applies to bystander observers. While the history given by a victim is important, the physician must remain influenced by scientific and forensic fact only, as their assessment dictates.

Many events in daily life stimulate more than one sensory modality, and neuroscientific research in the last several decades has revealed that interactions among sensory modalities are ubiquitous in human perceptual processing. The human perceptual system is bombarded with a variety of sensory signals at any given moment, and for this information to be useful in conveying information about the environment, the brain has to determine which of the sensory signals have been produced by the same source, and how to integrate the information from the set of sensory signals to achieve the most accurate and precise estimate of the object or event that gave rise to them. Recent research shows that Bayesian causal inference can explain multisensory perception in a variety of tasks, domains, and conditions and, therefore, it appears that Bayesian causal inference governs multisensory perceptual processing in general (2,3).

In this framework, if the sensory signals are more or less consistent, the brain will likely infer a common cause for the signals and integrate them. Prior expectations also produce a bias for inference, and act like an additional sensory input weighing in the process. While Bayesian inference is statistically optimal (i.e., it minimizes a cost function, such as the average squared error), it can also produce illusions in certain conditions where there is an inconsistency between sensory signals, and yet there is sufficient evidence of a common cause. For example, when a signal flash is paired with two “beep” sounds, if the temporal and spatial attributes of the visual and auditory signals are fairly consistent, this can give rise to the illusory perception of two flashes. Similar illusions can happen in the tactile modality if taps on the finger paired with inconsistent number of flashes or beeps. Indeed, Bayesian causal inference has been shown to account for these and a variety of other perceptual illusions (2,4–7).

Therefore, it is expected that a similar interaction would take place for sensory signals associated with an electric shock. Because an electric shock is often accompanied by certain visual, tactile, and auditory sensations, the expectation of electrical current in the presence of such sensations would be high, and can produce the illusory perception of a shock. Because most subjects have minimal experience with electric shocks, the “correct” perception is not known. Therefore, it is easy for the brain to adopt those past reports and ascribe an electrical cause to a circumstance it reasons to be otherwise consistent.

*Other Sources of Confusion*

Financial self-interest may also introduce a bias in victim recollection; this is reported to be a small effect in many countries, including Australia (8). However, it is a possibility that must be borne in mind, especially in the United States, with its minimal limits on litigation. Nonetheless, a claim of injury for which no objective evidence of significant current passage can be found does not inevitably imply malintent. Shock victims may also perform Internet searches to learn about typical electrical injury symptoms that they apply to themselves.

Due to the proliferation of electric automobiles and electrical energy storage batteries, direct current (DC) shocks are no longer just a theoretical concern. DC has significantly different effects on the body compared to alternating current (AC). Because DC is significantly safer, in many respects, than AC, this distinction must be kept in mind. Our case 4 involved confusion between DC and AC effects. Finally, the current path is sometimes very localized (typically within the hand). Evidence of a localized burn often leads to the mistaken perception that there has been a dangerous body current. This was an issue in our case 6.

A challenge in nonfatal injury cases is understanding possible causation of alleged nonanatomical symptoms. Did multisensory misperception lead to a sincere perception of a nonexistent shock? Conversely, when neurological tests, such as nerve conduction studies, return normal results, it may be that the testing was not at the true site of an injured body element.

Answering these questions often requires an understanding of the current path, the level of electrical current, and the duration of the exposure. The power of melding this knowledge with medical understanding will be appreciated. Otherwise, it is absolutely important to consider the investigation of an electrical incident to devolve to a skilled team rather than a single individual. We will analyze seven such incidents in this article.

We first consider five cases in which the subjects were startled by a perceived shock that most likely did not deliver electrical current to any part of the body. Calculations of the current and path were critical in understanding the nature of the shock and allocating causality between the shock and a history of chronic disease or previous trauma. It was also important to catalog and evaluate simultaneous sensory stimuli for the consideration of possible multisensory misperception. In two cases (6 and 7), there was a localized current within the hand. In all seven cases, our analysis suggests that no current was passed through the body.

*Analysis Approach*

We use the following sequence for analyzing such cases:

1. Determine body pathway
2. Estimate body impedance. The hand-to-hand impedance is typically 4000 Ω (confidence limit [CL] 2400–6900 Ω) for dry (or fresh-water wet) intact skin. This is reduced to 2300 Ω (CL 1700–3100 Ω) with salt-water or heavy sweat (9). The hand-to-foot impedance is about 20% less. Dry calloused palms used in manual labor may have an impedance of 50,000 Ω or higher (10).
3. Determine source voltage
4. Determine source impedance
5. Calculate delivered current via Ohm's law. A hand-to-foot current of 40 mA is considered safe for ventricular fibrillation (VF); for hand-to-hand this rises to 100 mA. Sustained currents >15 mA can have psychological consequences.
6. Ignore available current, as it is largely confounding in most cases. We ensure that the current calculated falls within the available current from the device. Once this is established, the available current rating is of no further use.
7. In cases of 0 (zero) current, considering Bayesian inference with multisensory stimuli.

Note that the absence of fresh wounds generally indicates the absence of anatomical electrical injury, as the skin exhibits the greatest pathological response to nonfatal electrical shocks (11,12). There are two critical nonanatomical clarifications with this rule: 1) VF can be induced without causing burns about 40% of the time (13,14), 2) psychological sequalae are often seen with prolonged shocks of >15 mA having a "no-let-go" immobilizing response (15).

The cases are summarized in Table 1.

## CASE REPORTS

*Case 1*

*Presentation.* A middle-aged female was attempting to remove a vertical conduit from ground. The moving conduit breached the insulation for a 220 VAC 60-Hz feeder line that had been incorrectly reported to be disconnected (2× 110 VAC "hot" lines and a neutral). A 110-VAC line contacted the neutral and the victim heard a loud "electrical" noise and reported "fire" coming from the pipe. The 2.5-ampere primary (street) transformer fuse was blown, suggesting that the secondary current exceeded 80 amperes due to the 32:1 transformer winding ratio.

The victim was startled by the contact and later complained of various neurological symptoms. Initial attention was focused on the 80-ampere capability of the source.

*Analysis.* As the subject was wearing thick-soled athletic shoes and standing on dry soil, there was no completed circuit.

The subject did not actually receive a perceptible current but probably had a Bayesian inference multisensory integration response (16). The peak current, before the power-line fuse blew, was 100–200 amperes, which is comparable to arc-welding currents. Arc welding produces extremely bright light requiring safety goggles. Typical isotropic sound intensity is 90 dBA at 1 m from a welding arc. The light and sound reflecting up the conduit towards the subject would have been impressively high. It is entirely possible that she honestly formed the perception of an electrical current because she was startled by two other sensations related to electrical activity. Namely, auditory and visual correlates of electrical activity.

*Cases 2 and 3*

A 62-year-old electrical engineer, specializing in electrical safety (author PEP) was working to make measurements of the voltage in a compact three-phase 220V supply. He held voltage probes by the furthest end from the tips and tried to measure the voltage down this supply without either shorting the supply to ground or contacting the mains circuit with his fingers. There was a small group of onlookers watching this. As he was making a measurement, his pager buzzed reminding him to review an incoming message. Thinking that he had received an electric shock, he threw the probes high into the air and stepped backwards from the device being tested. Those standing around asked if he had received an electric shock and, at first, he was not sure until his pager vibrated again. After a short coffee break to get past the reaction, testing was resumed and, subsequently, completed successfully.

Author MWK was involved in a household electrical repair when his mobile phone began vibrating for an incoming call. He briefly formed the impression that he had received an electrical shock. That misperception quickly passed when the author released the electrical wires and realized that the phone was still buzzing in his back pocket. Had that vibration been much shorter in duration, reality would have been more difficult to discern.

*Case 4*

*Presentation.* In 2015, a 26-year old Indiana welder was startled when the handle on his welder had a water-cooling failure. This melted the insulation producing

**Table 1. Summary of Cases**

| Case | Age, y/Sex | Source | Pathway | Presentation | Available Current, A | Sensation Confusion |
|---|---|---|---|---|---|---|
| 1 | 48/F | 110 V 60 Hz | None (possibly hands to body capacitance) | Complaints of neurological symptoms | 80 | Visual, auditory |
| 2 | 62/M | 230 V 60 Hz | None | Startle | 20 | Vibratory |
| 3 | 65/M | 110 V 60 Hz | None | Startle | 15 | Vibratory |
| 4 | 26/M | 60 V DC | None | Complaints of neurological symptoms | 220 | Burn pain |
| 5 | 4/M | 110 V 60 Hz | None | Second-degree superficial burn, blister | 15 | Visual, burn pain |
| 6 | 30/M | 440 V 60 Hz | Between knuckles | Brain injury, fatigue | 50 | NA |
| 7 | ~45/M | 230 VAC | Finger to thumb | No-let-go | ~20 | NA |

A = amperes; F = female; M = male; DC = direct current; NA = not applicable.

intense and objectionable fumes. He described being shocked and burned by the exposed wire after being frightened by noxious smoke inside his welding helmet. The welder was set to 220 amperes in DC electronegative mode and there was much concern about this high available current.

The welder described feeling an electric shock with an unusual pattern of delayed sensations. He told an emergency department nurse that the return path was his left arm, which was leaning against a metal pole. The emergency department records state:

> He was welding—at that time he was leaning against a pole when he felt a shock to his right arm. He noticed a scratch and then the smoke from his cable. He removed his mask and garment and ran to the other side of the building—turning off the welder and the electricity feeding the welder. He was "shook up" and had some tingling in his right arm but didn't think much of it.

Two days later he described pains in his chest and right arm to emergency department staff. The hospital record states that there were no burns. In a deposition, he described the sensation sequence as:

> It hooked me in. It pulled both my arms into my body … It started in my right arm about mid-forearm top. Then after it hit me there, it hit on my left steel toed boot.

The subject later complained of sharp pains in the forearm and numbness in two fingers. He was seen by an electrical-injury physician specialist who described the recollections as consistent with the no-let-go phenomenon and the symptoms as consistent with nerve damage in the right arm.

*Analysis.* The subject was wearing personal-protective gear, including boots, long-sleeved cotton shirt, welding gloves, and a helmet. He was possibly also wearing welder's protective sleeves. At the time of the incident, he was sitting on a stool. There was no apparent current path as his body—except for the occipital region—was completely insulated against low-voltage shocks. The welding unit produced 80 VDC open-circuit, but the subject described the incident as occurring during a 220-ampere weld, which reduced the voltage to approximately 60 VDC. There was no clothing damage found to provide an insulation gap required for an electrical circuit. The ambient was room temperature with low humidity and the clothing was not sweaty. We recreated the incident with the identical equipment and clothing. The melting-insulation smell was impressively revolting and disturbing but there was no current passed.

The most likely explanation was that the individual was surprised by the noxious fumes and the high-temperature sensation on his forearm. He probably formed a Bayesian multisensory misperception of an electrical shock (17).

Despite its inelegant term, the no-let-go phenomenon is well documented and understood. With a sufficient level (>15 mA) of AC current through the arm, the arm motor neurons are all captured. The 60-Hz frequency is rapid enough to tetanize slow-twitch muscle and nearly tetanize fast-twitch muscle and the flexor muscles overpower the extensor muscles, leading to a tight grip and a unilateral decorticate posturing. If the electrical contact was in the palm then this response can lead to a prolonged and disturbing shock associated with post-traumatic stress disorder (15,18). While somewhat controversial, a no-let-go shock has also been associated with chronic pain and muscle weakness in the affected arm (19). At lower currents (>1 mA), the spinal withdrawal reflex (flexion of a limb toward the core based on spinal stimulation) occurs (20).

Later descriptions of no-let-go effects may have been based on Internet searches for electrical injury. However, DC does not create the no-let-go phenomenon because there is no repetitive stimulation of the motor neurons in the arm. There is a brief contraction when the current starts and ends, but volunteers are always able to let go, according to the Dalziel et al. study (21). This fundamental difference between AC and DC is also memorialized in the International Electrotechnical Commission (IEC) electrical safety standard 60479-1 (9).

*Case 5*

*Presentation.* In 2017, a precocious 4-year-old Georgia male used a metallic decorative punched-paper fastener to defeat a “childproof” 120-VAC outlet. This resulted in a low-resistance fault that quickly heated the fastener before tripping the 15-ampere breaker. The high temperature burned the fastener varnish coating (and possibly also the outlet cover and socket), resulting in the soot deposits shown in Figure 1.

The child yelled “Mommy, owie!” and had a burn blister on the index finger of the dominant (right) hand, as seen in Figure 2. The mother, a practicing medical professional, was aware of the literature on delayed neurological sequelae from electrical injuries. She expressed great concern for the child’s prognosis.

*Analysis.* The outlet was not protected by a ground fault interrupter/residual-current device system. However, the child was seated on dry carpeting and the left hand was not in contact with any conductive surfaces, therefore, there was no body circuit. Depending on which contact was made first, the child’s body may have been at a potential of 120 VAC. As soon as the circuit was completed then the button was at a potential of 60 VAC due to the voltage division before the circuit breaker tripped.

We were able to reassure the mother that no current passed into the child’s body so there was no opportunity for nerve damage. The burn was purely thermal and not electrical in nature. At a 2-year follow-up, the child continues to be precocious and adventurous.

*Case 6*

*Presentation.* In 2011, a Minnesota repairman contacted some fuses in a 3-phase 480 VAC power panel for an overhead crane (Figure 3). The power-panel main fuse was 50 amperes and therefore there was a high available current. According to his incident report, he was holding a new fuse in his left hand when he contacted 2 or 3 installed fuses. The man later described symptoms of weakness and numbness in his left arm and other neurocognitive deficits and brain injury. He also described minor burns on the back of his knuckles.

He stated, “as my left hand became close to the panel it felt as if my hand got sucked into the panel across all three phases.” The reported sensation (of the hand being “sucked” in) is not consistent with the known effects of electrical shocks to dorsal surfaces of the body because the flexor muscles overpower the extensor muscles. However, it is consistent with a superficial understanding of the no-let-go phenomenon. In sworn testimony, the repairman was inconsistent about whether his right hand or arm was in contact with anything in order to provide a pathway for current through the body. He was wearing long pants and shoes.

*Analysis.* With his left hand holding the fuse, the dorsal finger surfaces would have made a connection between a pair of fuses at different voltages. This would tend to quickly burn off the stratum corneum (thin skin-shedding layer) near the contact spots (22). This, in turn, would have led to the reported minor charring on the skin surface just before the spinal reflex pulled the hand back (20,23–25). This current did not flow outside of the fingers and therefore there was no mechanism for any type of injury outside of this minor charring to some knuckles.

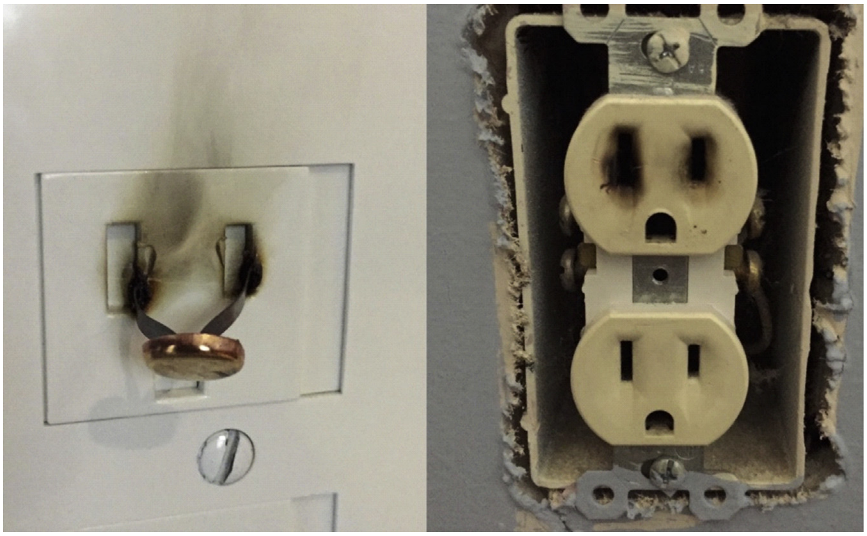

**Figure 1. Burn damage from insertion of metallic paper fastener into 120 VAC outlet.**

**Figure 2. Burn blister on index finger.**

While the evidence suggests no body current, we also analyzed the possibility that the right hand was in direct contact with some grounded metal, such as the metal safety railing. The voltage between any of the 480-volt contacts and ground (or neutral) is given by:

$480\ \text{V} \div \sqrt{3} = 277\ \text{V}$

The subject testified that he had "really" dry hands that day, which is consistent with the incident month of December, which is a time of low humidity in Minnesota. The body-to-hand resistance of dry palms is typically 50 kΩ. We also assumed conservatively that the damage to the stratum corneum (of some left knuckles) happened before the subject could reflexively pull back his left hand. This would lower the resistance on the left side of the body to 1300 Ω for this voltage (9). This would give a total resistance of 51.3 kΩ and Ohm's law provides a current of:

$= 277\ \text{V} \div 51.3\ \text{k}\Omega = 5.4\ \text{mA}$

This would be a perceptible current, but well below any safety limits (9). It is also far below any currents that could cause nerve damage (26–28). It is also below the 15-mA current level that causes muscle contractions


**Figure 3. 440 VAC 3-phase fuse bank contacted by back of fingers.**

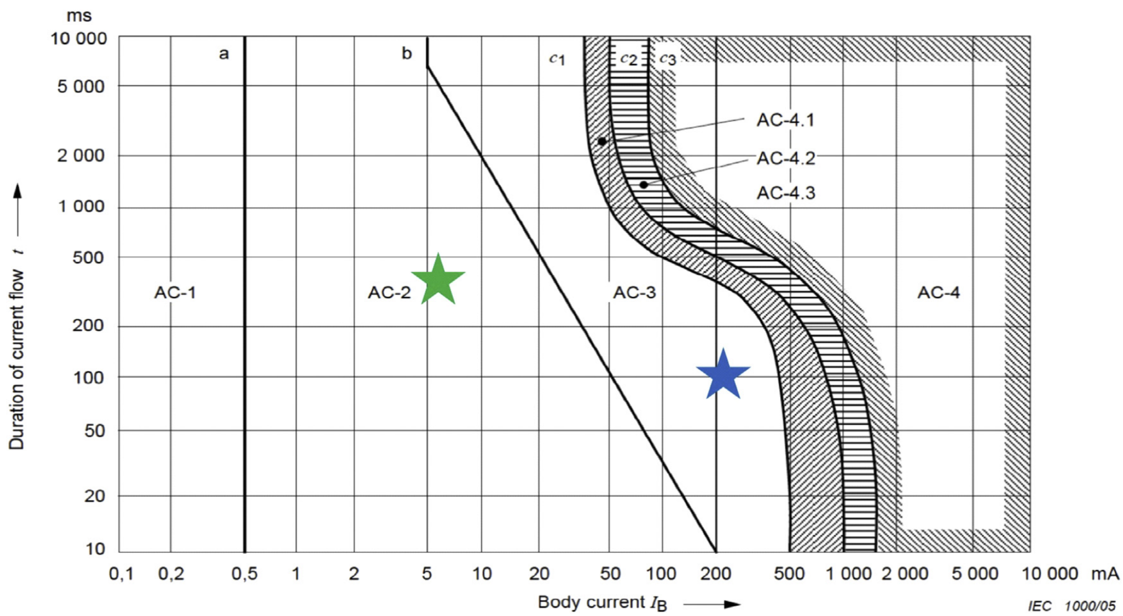


**Figure 4. IEC 479 chart of effect zones. Oblique line b represents the threshold for respiration interference. Curved lines c1, c2, and c3 are the thresholds for low, 5%, and 50% risk of ventricular fibrillation induction.**

with longer exposures (29). The spinal withdrawal reflex would pull the left hand back in about 300–500 ms (0.3–0.5 s) (20).

The combination of the low current (5.4 mA) and the duration (0.3–0.5 s) puts the shock in the AC-2 safe zone (green star) taken from the IEC safety specification, as seen in Figure 4 (9). Even the possible 5.4 mA of arm current most likely did not occur because the current was very localized between the outer portions of the left knuckles. Note that the safety-standard time-current zones only indicate safety for physical consequences, and should not be interpreted as applying to psychological symptoms.

We also considered a worst-case scenario where the hands were wet with sweat and the right hand was tightly gripping the railing. Assuming a worst-case hand-to-hand impedance of 1 kΩ, this would have produced a current of 277 mA. With such a strong current there is direct activation of the motor neurons and eventually direct activation of muscle spindles with a 100-ms retraction response due to the dominance of the flexor muscles (30). The shock would then be represented by the blue star in Figure 4 and still in a safe zone.

*Case 7*

*Presentation.* An approximately 45-year-old test technician was troubleshooting a large electronic system and the problem seemed to be in a 15-V secondary circuit board. The specific circuit was on a small, hand-sized circuit board that was attached to a similar-sized aluminum plate via insulated standoffs, but also had another similar-sized 230-V mains board attached on the back side. The entire assembly was removable for servicing while powered and operating and, in this case, the technician had pulled it out live for troubleshooting. Holding the unit with the 15-V circuit up meant that the 230-V mains board was touching his hand. He made contact between his wedding ring on his 4th finger and his thumb plus nearby palm, which was touching the ground circuit along the edge of the board, which was also connected to the aluminum structural element to which the boards were mounted. Immobilized, unable to let go, all he could do was grunt, which alerted another nearby technician who came to see what was going on. Upon seeing the situation, the other technician threw the circuit breaker powering the unit and the test technician was able now to let go of the equipment.

No visible burns or long-term sequelae were reported.

*Analysis.* This is a very interesting and instructive case, as it shows that the no-let-go phenomenon can be exhibited without a current through the full arm. The classic Dalziel et al. studies used a current through the length of the arm (21,31). The main muscles moving the fingers are all in the forearm and not in the hand. However, there are small accessory muscles in the hand (palm adductors, dorsal adductors, and lumbricals), each of which has a role in finger movement. This witnessed case demonstrates that the contraction of the hand can be caused by a very local current.

Sances et al. found that a current density of <100 mA/cm$^2$ will not lead to burns even with a long-duration exposure (up to 10 min) (32). We estimate that the wedding ring and thumb contact provided a contact area of 3–6 $cm^2$. Based on the absence of burns, this suggests that the current was below the 300–600 mA (= 100 mA ÷ 3 $cm^2$ and also 6 $cm^2$) range. Finally, using Ohm's law and the source voltage of 230 V suggests that the impedance was above the 380–770 Ω range, which appear reasonable with fairly dry hands.

## DISCUSSION

We believe that this article is the first case series of atypical electrical accidents to present the concept of illusory perception of an electric shock due to Bayesian inference in multisensory perception. Subjects 1–4 appear to have falsely perceived a shock due to this phenomenon. Subject 1 saw and heard the electrical arc, while subject 4 smelled the electrical insulation fumes and felt the heat of the wire. The available current was enormous, while the actual current was essentially 0 (zero). Thus, consideration of the available current was decidedly unhelpful, indeed of no relevance.

In the first incident, a quantitative analysis established that the shock body current (most likely 0 amperes) was below levels of perception and well below levels required for nerve damage. It also was able to explain the probable shock perception of the subject by a Bayesian multisensory response. In case 5, the subject received a thermal burn but no current was conducted by his body—even locally. In case 6, the subject fortuitously received only a painful burn via a localized current between his knuckles.

In case 4, the subject most likely received no electrical shock. However, due to the sudden exposure to noxious "electrical" burn fumes, and heating to his arm, he had probable shock perception from a multisensory misperception. Initial analysis focused on the 220-ampere available current and this distracted further analyses from considering the safe low voltage and the insulation from clothing and boots.

Victims are often quite uncritical in what they may read in Internet searching for electrical injury symptoms. This is not surprising with a void of information able to be provided medically. The application of inappropriate research is a consequence, throwing a great responsibility onto the physician not to be side-tracked and dissuaded from proper scientific analysis. While there is much still to be known about electrical injury, for example, the relationship between psychological symptoms and the location and size of a shock, the emphasis is strongly on skilled teamwork to obtain an honest and scientific appraisal of the shock using methods as shown here.

Available current is usually irrelevant and overemphasized. It can also distract from a careful analysis of the delivered current and pathway. This is an example where focus on an irrelevant parameter can obfuscate a search for truth.

Determination of the current pathway and calculations of the amplitude and duration of the shock can be critical for understanding the limits and potential causation of electrical injury. Skilled examiners are needed to assess this, as medical practitioners are very poorly trained in these matters. The consequence of this poor training is often lack of ability to assist (treat or alternatively reassure) a victim. Alternatively many practitioners are unwilling to admit a lack of knowledge and perpetuate patient beliefs by providing inaccurate, if not erroneous, information.

## WHY SHOULD AN EMERGENCY PHYSICIAN BE AWARE OF THIS?

Symptomology seen as corroborating may actually be confounding. Witness and survivor descriptions of electrical shocks are fraught with subjectivity and misunderstanding. Available current is usually irrelevant and overemphasized, such as stress on a 100-ampere welding source, which is orders of magnitude beyond lethal limits. History can also be biased for a number of reasons. Bayesian inference in multisensory perception can lead to a subject sincerely believing they had experienced an electrical shock. Determination of the current pathway and calculations of the amplitude and duration of the shock can be critical for understanding the limits and potential causation of electrical injury.

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## REFERENCES

1. Singerman J, Gomez M, Fish JS. Long-term sequelae of low-voltage electrical injury. J Burn Care Res 2008;29:773–7.
2. Kording KP, Beierholm U, Ma WJ, Quartz S, Tenenbaum JB, Shams L. Causal inference in multisensory perception. PLoS One 2007;2(9):e943.
3. Shams L, Kim R. Crossmodal influences on visual perception. Phys Life Rev 2010;7:269–84.
4. Shams L, Ma WJ, Beierholm U. Sound-induced flash illusion as an optimal percept. Neuroreport 2005;16:1923–7.
5. Wozny DR, Beierholm UR, Shams L. Human trimodal perception follows optimal statistical inference. J Vis 2008;8(3). 24.1–11.
6. Samad M, Chung AJ, Shams L. Perception of body ownership is driven by Bayesian sensory inference. PLoS One 2015;10(2):e0117178.
7. Peters MA, Ma WJ, Shams L. The size-weight illusion is not anti-Bayesian after all: a unifying Bayesian account. Peer J 2016;4:e2124.
8. Andrews CJ. Further documentation of remote effects of electrical injuries, with comments on the place of neuropsychological testing and functional scanning. IEEE Trans Biomed Eng 2006;53:2102–13.

9. International Electrotechnical Commission. Effects of Current on Human Beings and Livestock, CEI/IEC 60479-1: General Aspects. 5th edn. Geneva, Switzerland: International Electrotechnical Commission; 2016.
10. Poticha SM, Bell JL, Mehn WH. Electrical injuries with special reference to the hand. Arch Surg 1962;85:852–61.
11. Skoog T. Electrical injuries. J Trauma 1970;10:816–30.
12. Hunt JL, Mason AD Jr, Masterson TS, Pruitt BA Jr. The pathophysiology of acute electric injuries. J Trauma 1976;16:335–40.
13. Fish R. Electric shock, part I: physics and pathophysiology. J Emerg Med 1993;11:309–12.
14. Wright R, Davis J. The investigation of electrical deaths: a report of 220 fatalities. J Forensic Sci 1980;25:514–21.
15. Kelley KM, Tkachenko TA, Pliskin NH, Fink JW, Lee RC. Life after electrical injury. risk factors for psychiatric sequelae. Ann N Y Acad Sci 1999;888:356–63.
16. Yeomans JS, Li L, Scott BW, Frankland PW. Tactile, acoustic and vestibular systems sum to elicit the startle reflex. Neurosci Biobehav Rev 2002;26:1–11.
17. Thesen T, Vibell JF, Calvert GA, Österbauer RA. Neuroimaging of multisensory processing in vision, audition, touch, and olfaction. Cogn Proc 2004;5(2):84–93.
18. Thomee S, Jakobsson K. Life-changing or trivial: Electricians' views about electrical accidents. Work 2018;60:573–85.
19. Radman L, Nilsagard Y, Jakobsson K, Ek A, Gunnarsson LG. Electrical injury in relation to voltage, "no-let-go" phenomenon, symptoms and perceived safety culture: a survey of Swedish male electricians. Int Arch Occup Environ Health 2016;89:261–70.
20. Javan B, Zehr EP. Short-term plasticity of spinal reflex excitability induced by rhythmic arm movement. J Neurophysiol 2008;99:2000–5.
21. Dalziel CF, Ogden E, Abbott CE. Effect of frequency on let-go currents. Electric Engineer 1943;62:745–9.
22. Kroll MW, Panescu D. Physics of electrical injury. In: Ho JD, Dawes DM, Kroll MW, eds. Atlas of Conducted Electrical Weapon Wounds and Forensic Analysis. New York: Springer; 2012:25–45.
23. Goldberg RB. Muscle innervation and the Hoffman reflex. Am J Sports Med 1983;11:273–5.
24. Guiheneuc P, Ginet J. [Study of the Hoffman reflex obtained at the level of the quadriceps muscle of normal human subjects]. Electroencephalogr Clin Neurophysiol 1974;36:225–31.
25. Misiaszek JE. The H-reflex as a tool in neurophysiology: its limitations and uses in understanding nervous system function. Muscle Nerve 2003;28:144–60.
26. Fedorov V, Livshitz L, Kostecki G, Efimov I. Electroporation of cardiac and nerve cells. In: Kroll M, Ho J, eds. TASER Conducted Electrical Weapons: Physiology, Pathology, and Law. New York: Springer-Kluwer; 2009:187–200.
27. Ritchie AE. The electrical diagnosis of peripheral nerve injury. Brain 1944;67:314–30.
28. Ritchie AE. Electrical diagnosis of peripheral nerve injury. Spec Rep Ser Med Res Counc (G B) 1954;282:239–62.
29. Dalziel CF, Lee WR. Reevaluation of lethal electric currents. IEEE Trans Industry Gen Appl IGA-4 1968;(5):467–76.
30. Carter AO, Morley R. Effects of power frequency voltages on amputated human limb. Br J Ind Med 1969;26:224–30.
31. Dalziel CF, Massoglia FP. Let-go currents and voltages. Trans Am Inst Elect Eng 1956;75:49–56.
32. Sances A Jr, Myklebust JB, Larson SJ, et al. Experimental electrical injury studies. J Trauma 1981;21:589–97.
33. Kroll MW, Ritter MB, Perkins PE, Shams L, Andrews CJ. Perceived electrical shock and Bayesian inference with multisensory stimuli. Am J Emerg Med 2018; https://doi.org/10.1016/j.ajem.2018.07.042. [Epub ahead of print].