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A multidisciplinary forensic analysis of two lightning deaths observed in South Africa

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ABSTRACT

While in-depth studies of lightning deaths can be found in the literature, rarely do such investigations they utilize a multidisciplinary approach, analysing both the medical and electrical aspects of a case. Even more rare, is to find such studies on cases from the developing world such as Africa and South-East Asia - particularly in tropical countries with very high lightning exposure. This paper details the forensic investigation of two lightning deaths that took place during a weekend in February 2020, in South Africa. One event was eye witnessed and the other was not (Case A and B). The investigation involves multidisciplinary forensic examination including case histories, site analysis (including soil resistivity measurements), medical autopsies, lightning location system data analysis and voltage gradient estimations. In both cases, lightning is determined to be the cause of death. In Case A, we confirm that the responsible flash must have attached within close proximity to the deceased, if not a direct strike and in Case B we confirm direct strike as the most probable mechanism of death. The importance of clothing examination in the forensic studies of lightning victims is noted along with a discussion of the lightning safety issues at play, and recommendations for avoiding such incidents in developing world countries.

1. Introduction

Lightning, a natural transient high current phenomenon, accounts for one of the largest atmospheric event related injuries in Africa. The annual death rate in the continent is in the order of thousands among which the majority are from underprivileged rural communities [1,2]. Current estimates see countries in Africa with more than 5 deaths/million/year and South-East Asia between 0.6 and 5 deaths/million/year. In contrast, developed nations such as the USA and Europe have rates below 0.5 deaths/million/year [3,4]. It should be noted that, while this is a function of developed infrastructure and lightning safety awareness, exposure also plays a role with some of the highest lightning densities occurring in tropical regions such as central Africa and South-East Asia [5,6]. Although lightning deaths are common in many tropical countries, in depth studies from these regions on the medical and physical aspects of the cause of death - such as found elsewhere [7–12] - are rare to find in the literature. One major reason for such rarity is the accessibility of multiple information such as incident environment details, witness statements and autopsy reports to a single research party. Even more rare, is to find multidisciplinary studies such as that conducted by *Fan* et al. in China, examining both medical and electrical aspects [13]. Such case studies play a vital role in identifying the injury mechanism, cause of death and risk factors which in turn are highly significant in developing public safety modules.

This paper deals with the multidisciplinary forensic analysis of two cases of lightning related deaths and forms part of a larger study conducted by a research team that comprises a pathologist, engineers and physicists. The study takes place in the city of Pretoria (also known as the city of Tshwane) and surrounding areas, which is found in the Gauteng province of South Africa. The geographic area selected for the project and the locations of the two incidents discussed here is shown in Fig. 1. The area has between 40 and 70 thunderstorm days per year and a high ground flash density with 14–18 flashes/km^2/year [14]. It has many concentrated clusters of communities with low socio-economic status, of which people are regularly engaged with outdoor activities in low-grown open areas. Most of the community houses and other sheltering structures in such landscapes are not protected against lightning strikes. Thus, the area records relatively high lightning injuries on both human beings and livestock.

The two cases (referred to herein as Case A and Case B) discussed here occurred during the same weekend in February 2020, in the Pretoria region. The first case was eye witnessed. The second case was

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unwitnessed and the body was discovered two days later. The multidisciplinary approach taken is described and the outcomes of the investigations are presented in the following sections.

2. Lightning injury mechanisms

A single lightning flash typically consists of multiple impulse currents (termed first and subsequent strokes), each lasts for a few hundred microseconds with average amplitudes in the order of 20 kA for a negative first stroke, 12 kA for negative subsequent strokes and 35 kA for positive strokes [15,16]. In extreme cases, the peak values could be one magnitude greater than the respective average values. In some occasions, these transients may be followed by slow varying continuing currents that may exist for a few milliseconds. Continuing currents may have amplitudes in the order of 0.5–1 kA and may carry much larger energy content than the impulse component due to the large duration [15,16]. Given the currents involved in lightning events, lightning medical cases often exhibit characteristics associated with electrical injuries and deaths such as cardiac arrest and ventricular fibrillation amongst others [8,17–21].

Although the common perception is that lightning affects living beings when they have been directly struck by the flash, one may only need to be in the vicinity of the point of strike to receive lethal injuries or temporary disabilities that may even cause death. Lightning may injure or kill a living being through the following primary and secondary mechanisms [22–24]:

- Direct strikes: A person in an open field and being the tallest object in the vicinity may be the subject of a direct lightning strike. It is estimated that this accounts for 3–5% of lightning deaths and injuries.
- Side flashes: The voltage developed along a tall object while struck by lightning may lead to a flashover if a person is close enough. In such cases, part or all of the lightning may flow through the victim's body. This mechanism accounts for 25–30%.
- Touch potential: Similar to the side flash mechanism, part or all of the lightning may flow through a person's body if part of their body is in contact with a tall object that is struck by lightning while the other part remains in contact with ground. This mechanism accounts for 1–2%.
- Step potential: When the feet of a person are separated in the direction of increasing potential, a partial current may pass through the body due to the injection of current into earth from a nearby lightning strike. This is the most common mechanism and accounts for 30–50% of deaths and injuries.
- Upward streamers: As the lightning leader propagates from the cloud to the ground, typically carrying negative charge, it creates an intense electric field in the vicinity. Hence, many objects in the surrounding area start sending oppositely charged streamers towards the coming leader. Once one of these answering streamers is successful in meeting the leader, the others collapse. If initiating from a person, these collapsing leaders give rise to a small current through the body. Such current may most often paralyze the person; however, depending on the heart cycle that it passes through, even serious injuries or cardiac failure may result. 20–25% of injuries and deaths are estimated to be a result of the upward streamer mechanism.

Other, non-electrical injury mechanisms that may occur are:

- Proximity to the strike: The shock wave generated by lightning channels due to sudden expansion of air may damage the skin or ear drums when the person is very close to the point of strike. Furthermore the intensity of the light may cause vision impairment to humans or animals close by.
- Secondary effects: Falling from higher elevations due to momentary shock, falling of heavy materials from structures (detached due to lightning strike), falling of tree branches and shooting of split-fractions of lightning struck trees, burns and choking hazards due

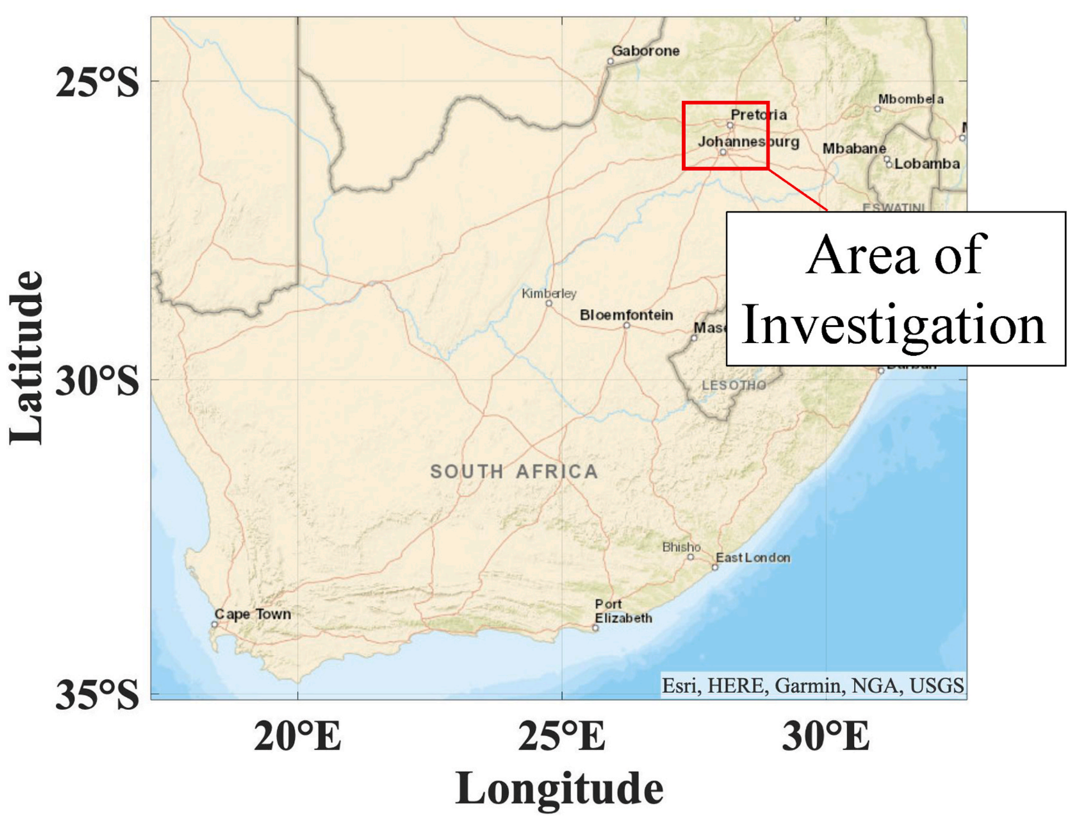


Fig. 1. A map of South Africa indicating the area of investigation for the project - the city of Pretoria (also known as Tshwane) found in the Gauteng province.

to volatile materials in the surrounding catching fire, shockwave from exploding substances and psychological trauma.

Significant work has been performed on understanding the current magnitudes necessary to affect the heart, and lead to injury and death. Many of these are based on the work of *Dalziel* et al., who relates critical current magnitudes to duration of current flow and to body weight [18]. This is also adopted in the SANS (South African National Standard) 60, 479: Effects of current on human beings and livestock standard, among others [25]. It is estimated that currents in the range of 0.75 mA–4 A can affect the heart and cause cardiac contraction, ventricular fibrillation and respiratory arrest if flowing directly through the chest cavity and heart [7,8,20,21].

There are numerous electrical models that describe the portion of current that would flow through the heart if current were to flow through the human body [8,16,21,25,26]. These models tend to describe the human body (and different parts) as 'lumped' resistances or (impedances) in order to estimate current magnitudes that would flow given exposure to different voltage levels. Estimating overall body resistance or impedance is also of interest, with values ranging greatly between 300 Ω to 5000 Ω depending on many factors but with frequency one of the key factors. The Institute for Electronic and Electrical Engineer's (IEEE) standard IEEE 80: Guide for safety in AC grounding recommends a simplified model of 1000 Ω for overall body impedance, which can then be used to calculate current magnitudes for varying voltage levels a body may be exposed to [26]. In general, these models note that only a small portion of current would flow through the heart if current were to flow from one foot to the other (as it occurs during the step potential mechanism). These amounts usually range between 2 and 4% of the current magnitude [19,25,26]. Much of the work on the effects of current flowing through the heart deals with electrocution from AC power frequency and durations for lightning are significantly lower, implying greater currents magnitudes are necessary to cause death during lightning events.

3. Methodology

The following section details the multidisciplinary methods used to perform the forensic analysis of the two cases. These include witness interviews, site inspections, medical autopsies, weather data analysis and an electrical (voltage and current) investigation. A lightning death is an unnatural death. As such, it is investigated according to the National Code of Guidelines for Forensic Pathology Services in South Africa (to be read in conjunction with the Regulations of the National Health Act 61 of 2003), also in accordance with the Inquests Act (Union Gazette Extraordinary, JRD, No 58, July 1959). Complete medico-legal autopsies were therefore performed on both bodies. Within a few days after the incident the research team visited the location of incidents, accompanied by an officer/s of the South African Police Service to conduct the site inspection and interviews.

3.1. Case histories

We first describe the context and history as the deceased was found. The observations obtained from interviews with eyewitnesses and other informants are recorded. The interviews were pre-arranged and the interviewees were identified with the help of the community leaders and the officers of the South African Police Service. Verbal interviews were recorded on video with the consent of the interviewee. The following predetermined points were raised:

- The relationship of the interviewee to the victim.
- A brief description of the background of the event as the interviewee could remember.
- The location of the interviewee at the moment of the lightning incident.
- What did the interviewee see/hear at the moment of the lightning incident?
- Whether there were any other people at the time observing the lightning incident.
- What did the interviewee and others around do immediately after the lightning incident?
- The status of the victim just after the lightning incident (was he conscious, did he speak or move body parts, was there any visible marks on his body, was he lying on the ground/sitting/standing/etc.).
- What did the spectators do (talk to the victim, lift him or make him stand/sit, give/sprinkle water, give CPR, give artificial respiration, did not touch him at all etc.)
- What happened after the lightning incident (someone called police/for medical aid, tried to take him into a shelter, did not do anything until the medical aid arrived etc.)
- Any changes happened/done to the location ('tampering') of the lightning incident since the accident occurred.

Apart from the formal interviewees there were informal communications with other onlookers. The accuracy and authenticity of the information given by one formal eye witness was cross-checked with the information provided by other formal and informal interviewees.

3.2. Site inspection

The site inspection includes the following activities:

- Identification of the exact location of the incident with the help of the pre-arranged eye witnesses.
- Visual inspection (and mapping) of the location of the incident for burn marks, soil disturbances, broken or damage marks on trees or any other objects in the vicinity.
- Estimation of distances to nearby objects from the point of incident and the dimensions of the objects.
- Photography and videography of the incident environment.
- Measurement of the soil resistivity profile of the location of the incident by a 4-pole Fluke 1623-2 ground tester (at 1 m, 2 m, 4 m and 6 m depths).
- Measurement of earth resistance of any nearby grounded object by Wenner method (by the same device described above).

3.3. Autopsy reports

The bodies underwent full medicolegal autopsy examination, in accordance with international practice and standard operating procedures [27–30]. This included initial observations about the state of the victim as found, an external examination of the body with clothes removed and an internal examination. The initial observations focussed on the state of the clothing of the deceased, in particular any damage to the clothing or jewellery that could indicate entry and exit points for current flow, tearing and torn clothes and indications of burning. These types of observations are consistent with lightning deaths and can provide insight into the mechanism of injury [23].

Both bodies underwent full radiography. The external examination then focussed on the presence or absence of marks on the skin. Once again, the presence or absence of injuries or wounds that could indicate entry or exit points for current flow was examined for, along with possible burn marks and Lichtenberg figures (another possible indication of lightning) [23]. Subsequent to the external examination, an internal autopsy was performed noting any injury or pathology to the internal organs, particularly rupture of the eardrums or signs suggestive of pneumomediastinum [31–33]. Histology and toxicology were also performed.

3.4. Lightning location system reports

The lightning ground flash occurrence reports were obtained from the South African Lightning Detection Network (SALDN) in order to identify the specific ground flashes that were relevant to the respective i, ncidents. Once the most likely ground flash is identified, its estimated multiplicity, polarity and peak currents of strokes can be obtained. The SALDN is operated by the South African Weather Service (SAWS) and consists of 24 Vaisala LS7000 sensors distributed in grid formation across South Africa, for optimal detection and geolocation of lightning events [14,34,35].

Fig. 2 shows the reported locations of all lightning flashes detected and grouped by the SALDN for a weekend in February 2020 in the Gauteng (North-East) region of South Africa (region shown in Fig. 1). Lightning detection networks detect and geo-locate individual strokes which are then grouped into flashes in accordance with the International Electrotechnical Commission standard on lightning detection networks, IEC 62858 - stroke detections within 500 ms and 10 km of each other, with no final stroke in a flash being detected more than 1 s later than the first stroke [36]. A total of 10,210 flashes were reported in the area for this time period. The progression through time is indicated in South African Standard Time (SAST) (UTC + 2 h) and three distinct storms can be seen - the first occurring on Friday (blue) progressing from West to East, the second on Saturday (green/yellow) progressing from South to North and the third on the Sunday (red) with much less activity occurring in the North region. No lightning activity was recorded by the SALDN on the following monday. The locations at which the victims were found (Case A and B) are indicated in the figure. We can see that both these locations experienced high lightning activity on the Friday and Saturday.

To identify the most likely flash responsible for Case A and Case B, the reported SALDN strokes are first grouped into flashes as above. We use the techniques described by Huddleston et al. and Hunt et al. which take into account the location errors (in the form of the provided confidence or 'error' ellipses) of each reported stroke in each flash [37–40]. In this way, we can calculate the probability of each flash having attached within an area where the victim was found (we use a radius of 25 m) and identify which flash (multiplicity, polarity, peak currents) was most likely responsible.

3.5. Estimating voltage gradients

One of the most common mechanisms of injury due to lightning is the step potential, where the lightning current dissipates radially outwards in the ground leading to a voltage gradient (or potential 'rings') being developed. If the soil resistivity is large, it is possible that the voltage gradient will be such that a significant voltage can be developed between the legs of a person. Fig. 3 provides a description of the step potential mechanism, where the resistances R_1, R_2, …,R_n and R_a represent the distributed resistance of the soil and are functions of distance and the soil resistivity, ρ.

Equation (1) gives the voltage V_{diff} developed between the legs of a person in the proximity of a lightning stroke to ground [26].

$$V_{diff} = \frac{\rho I_{peak}}{2\pi}\left(\frac{1}{x} - \frac{1}{(x+a)}\right) \quad (1)$$

I_{peak} is the peak current of a stroke, ρ is the soil resistivity, x the distance of the strike point from the victim and a is the distance between their legs, typically set at 1–0.5 m. This equation relies on the assumption that the soil is homogeneous and that current flows radially outwards equally from the strike point. Any irregularities in the soil, or the presence of any conductive materials (piping, cabling etc.) in or on the surface of the ground may change the situation, leading to equation (1) estimating the voltage incorrectly. Therefore, if we consider a step potential voltage of 1 kV and a human body resistance of 1000 Ω, we calculate a current of 1 A. We estimate that the heart would be exposed to at most 4% of this ie.

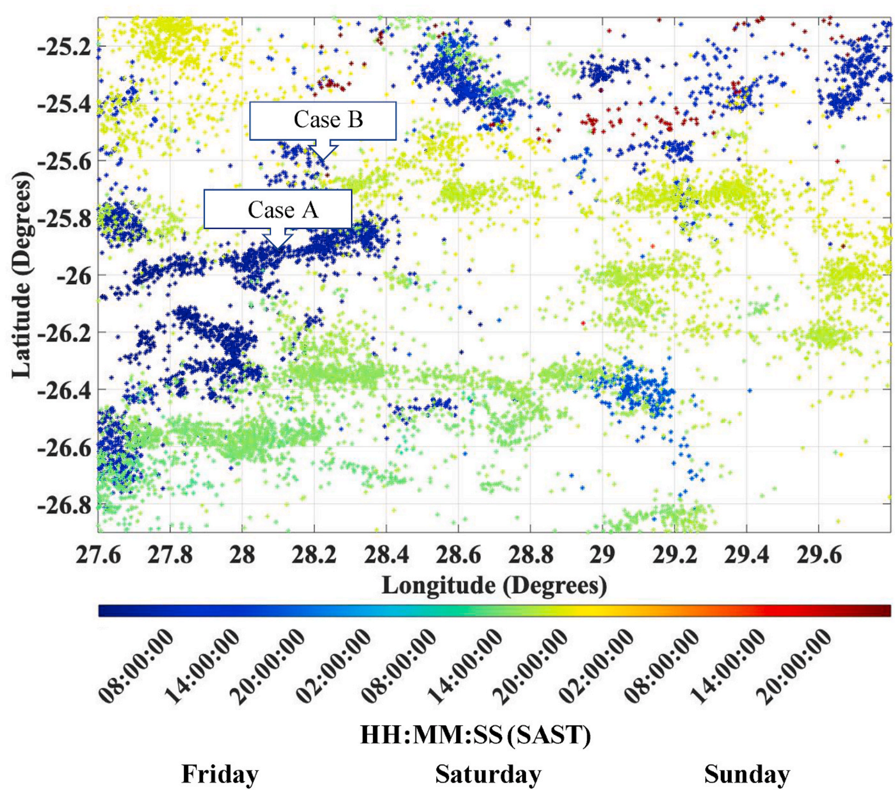


Fig. 2. South African Lightning Detection Network (SALDN) flash location reports for the weekend in February 2020 in the Gauteng area, South Africa. The location of Case A and Case B are indicated on the figure and the colour bar indicates progression in time of the storm.

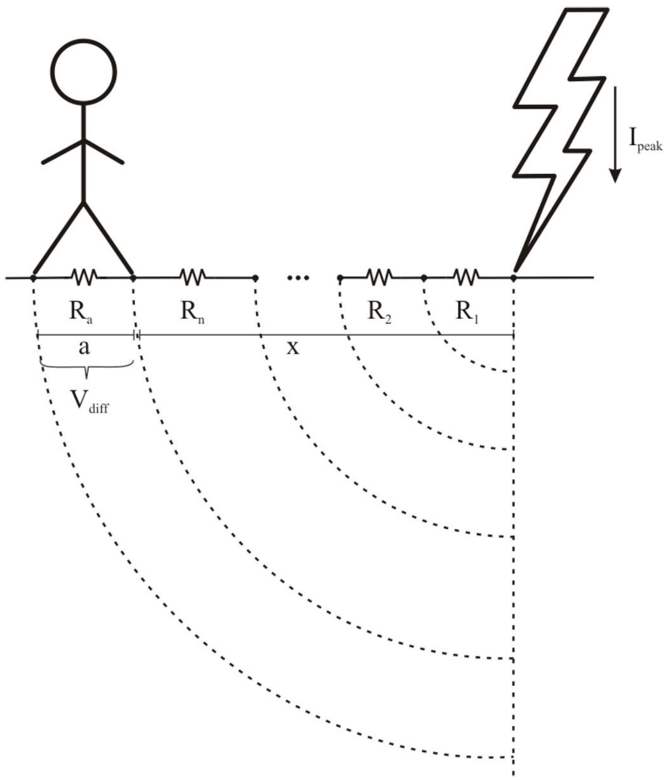


Fig. 3. Description of step potential injury mechanism and the estimation of the voltage developed between the feet of a person due to a nearby lightning strike.

40 mA. If we consider a lower estimate of human body resistance (say 600 Ω), this becomes 66 mA - current magnitudes that could result in death, depending on the duration of the lightning stroke.

4. Case analysis and discussion

The methodology described above is applied to Case A and Case B.

4.1. Case A

4.1.1. Case history

An adult black male was found dead in an informal settlement, South of Pretoria/Tshwane city on the Friday afternoon of a weekend in February 2020. The police received a call about the incident at approximately 16:30 SAST on the same day. Witness reports claimed that he was walking through the open area of the settlement while a storm (rain and lightning activity) was ongoing and that there was a loud ‘bang’ with the event itself being witnessed. The reports claimed that he was in conversation with a female fruit vendor, whereafter he was struck by lightning. Witnesses claimed the body was untouched subsequent to the event, until medical care/regional authorities approached. The investigation team was told by the neighbourhood that an on-surface electric cable that was running (probably an unauthorised power feed from a nearby street lamp pole to a dwelling in the vicinity) through the area, close to the point of accident, had subsequently been removed. The reliability of this information could not be confirmed.

4.1.2. Site description

The deceased was found in an open area of an informal settlement on a dirt road without any large structures in the immediate vicinity. The only tall structures nearby were light posts approximately 25–30 m from the location where the body was found. An overhead line was seen strung between the light posts. Fig. 4a shows an aerial view of the scene with the location where the body was found indicated as well as the relative position of the tallest structures - the light posts and the overhead line. The figure also indicates the supposed location of the electric cable that was possibly running across the ground at the time. Fig. 4b shows a panoramic photograph of the scene where we can see the open nature of the area. The light posts are indicated in the photograph as well.

The photograph in Fig. 4b also shows the soil resistivity measurements being taken. The results of the soil resistivity test is shown in Fig. 4c, where a plot of the resistivity against depth is provided (electrode spacing allows depth to be estimated as discussed previously). We can see that the resistivity of the soil at the scene ranges between approximately 80 to 200 Ωm and increases with depth. These resistivity values are larger than 25 Ωm but not significantly high as is often experienced in soil in South Africa [41,42]. The increasing resistivity with depth means that the majority of lightning current would flow closer to the surface. The resistance of the light posts was also measured as a ‘grounded object’ using the Wenner method as discussed previously. A resistance value of 2.54 Ω was obtained, which is consistent with electrode values in this type of soil and indicates that, if the light post was struck, lightning current would likely flow into the ground without great impedance.

4.1.3. Autopsy report

The victim was an adult black male. At the outset of the examination, the anterior aspect of the body was covered with sand and the clothing was wet. Observations made during external examination of the victim are shown in Fig. 5a–e. Observations regarding the clothing are as follows: light-brown trousers with multiple pockets (the right side of the trousers was torn-and-tattered) (Fig. 5a). The victim was wearing footwear and both showed signs of damage although neither shoe showed signs of entry on the underside. The right leather shoe was almost completely ruptured. The left leather shoe showed rupture; although to a lesser extent (Fig. 5b). Blue shorts (the white drawstring showed scorching, and there were tear-and-tatter marks anterior over the crotch region) (Fig. 5c). An orange-and-black golf shirt, with 2/3 lower buttons fastened (there was a 6 × 2 cm ‘tear’ of the upper neck region anterior, there were also tear-and-tatter marks and scorch marks, posterior). There was a brown leather belt, the 3 × 3 cm buckle showed signs of ‘metalization’. Black socks were present, the left sock showed a 7 × 4 cm ‘tear’ on the dorsal aspect, the right sock showed a tear overlying the big toe region.

On the body, the following observations were made: there was singeing of the pubic hair suggestive of open-flame or heat effect (Fig. 5d). There was a 3 × 2 cm fresh laceration located below the chin, most likely from a fall (blunt force trauma - a secondary effect). There was a 2*cm* horizontally orientated laceration located below the lower lip and examination of the inner aspect of the lower lip showed a 3 × 2 cm fresh laceration both of which were also most likely due to blunt force trauma from the fall. Also observed externally was a rupture of the left ear drum (Fig. 5e). No exit or entry wounds were found on either the upper or lower parts of the body, or any external injury marks or Lichtenberg figures. There were no injuries noted on the underlying skin and no exit or entry points were found on either of the feet or upper body area.

From the internal organ examination, the brain showed mild leptomeningeal congestion and weighed 1416 g. There was left petrous bone haemorrhage, probably in keeping with the ruptured left tympanic membrane (Fig. 5g). There was a left-sided tongue-bite mark present. There was a 2 cm horizontally orientated laceration located below the lower lip. A pneumomediastinum was present (Fig. 5f). The bladder contained approximately 80 ml of clear urine. Peri-bladder haemorrhagic congestion was present, which was most likely artefact in nature. Histological and toxicological examination showed no abnormalities.

The chief findings were in keeping with that of a direct lightning strike: rupture of the left ear drum [43] (Fig. 5e), torn-and-tattered

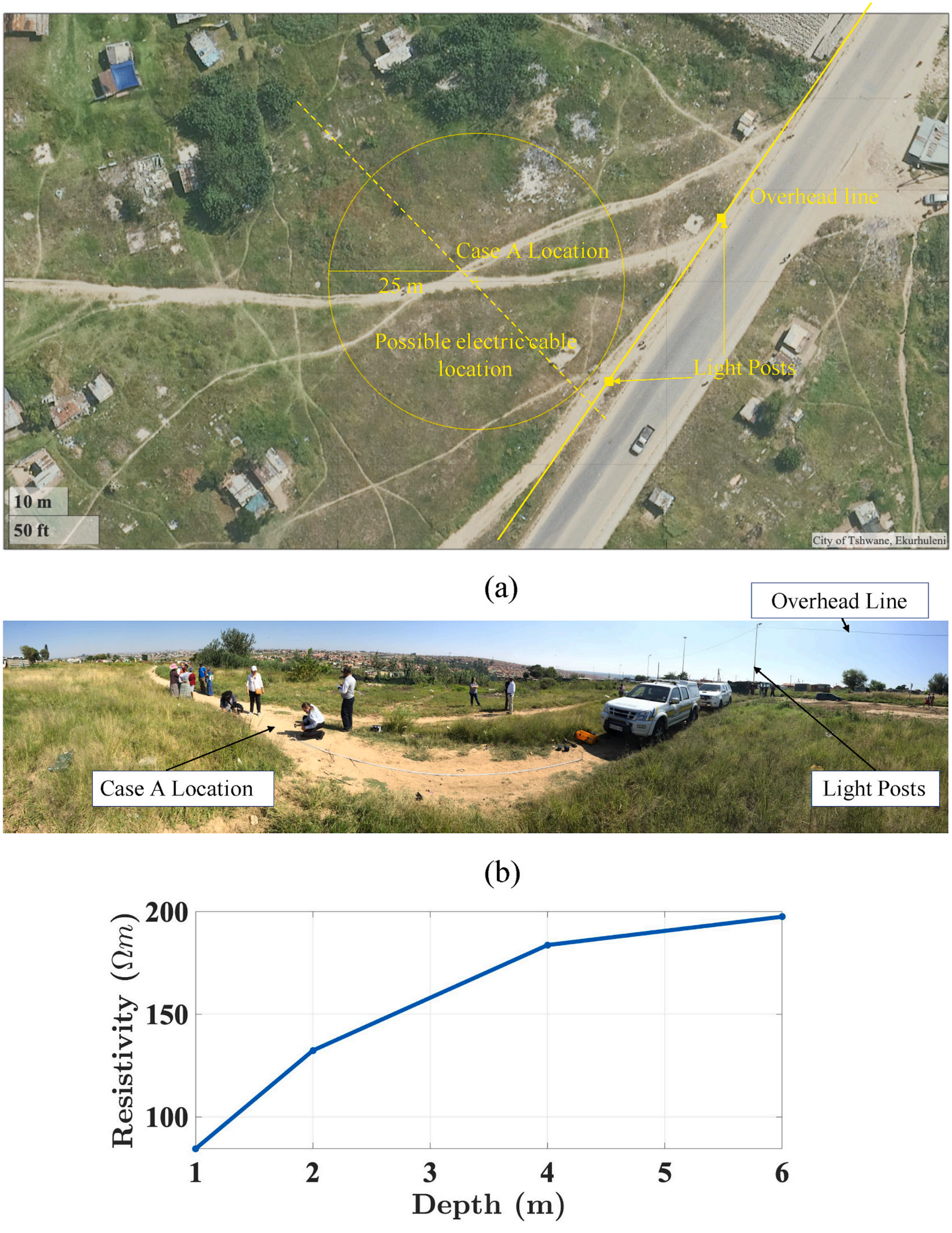


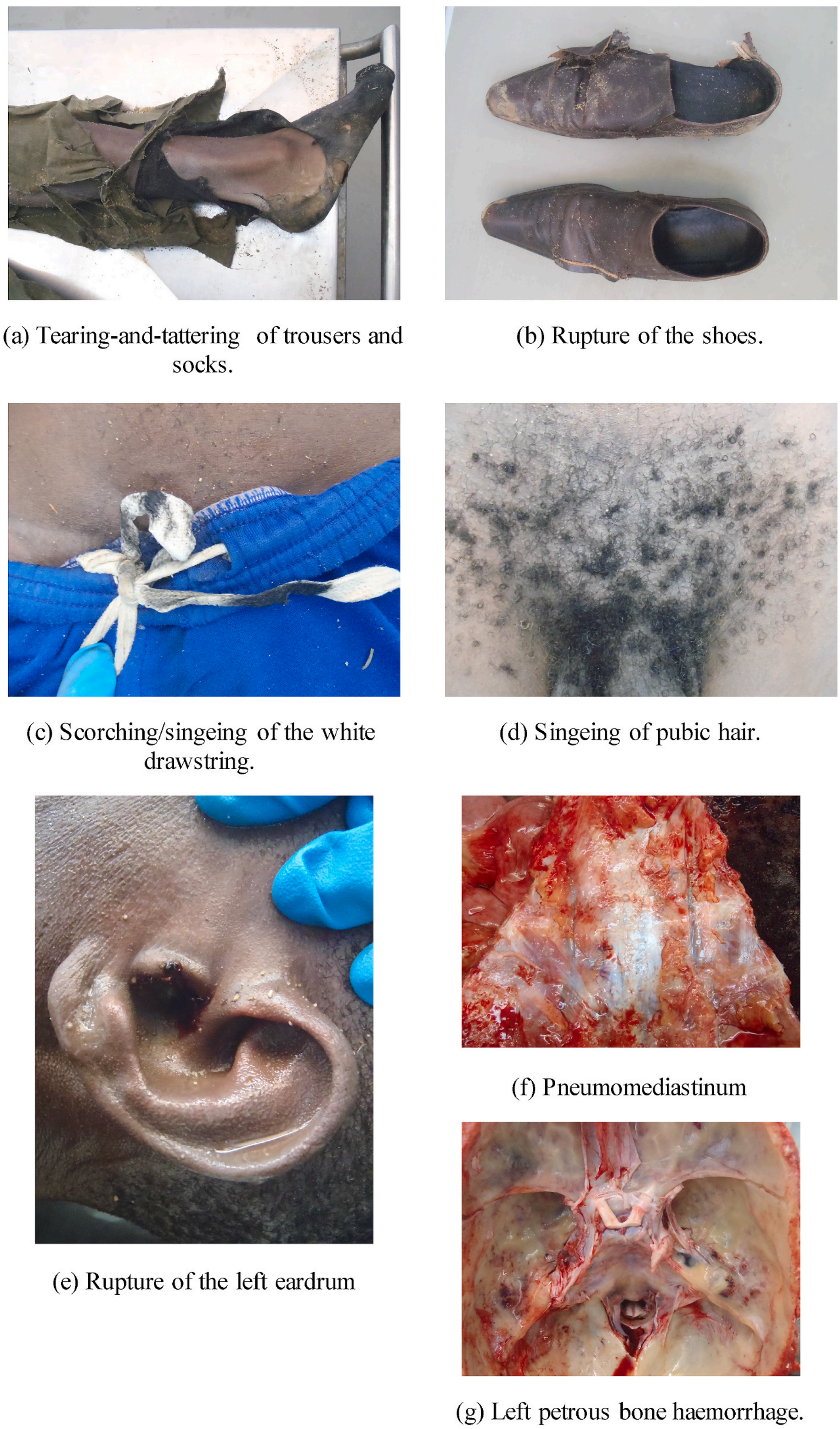
Fig. 4. Site description (a) site location of Case A with a 25 m radius indicated. Locations of the light posts, overhead line and the possible electric cable location are shown. (b) Panoramic photograph of site location while soil resistivity measurements are being conducted. Note the open area with the light posts (approximately 25–30 m from the body location) being the only tall structures in the vicinity. (c) Soil resistivity plot.

clothing (Fig. 5a), shoes showed signs of rupture (Fig. 5b), the presence of pneumomediastinum [31] (Fig. 5f), and the singeing of the pubic hair suggestive of open-flame or heat effect (Fig. 5d).

4.1.4. Lightning location system report

Fig. 6a shows the lightning flashes detected by the SALDN previously shown in Fig. 2 as reported distance from the location of Case A against time. Three distinct thunderstorms occurred on the Friday, Saturday and Sunday (blue, green/yellow and red respectively). We see that the lightning activity was much greater on the Friday and Saturday and passed over the location of Case A. It is also clear from the figure (indicated) that the storm on the Friday had many lightning events reported very close to the location of Case A at approximately 14:00:00 SAST. 6 Flashes were reported within 1 km of the location.

To discern the most likely flash that could be responsible, we calculate the probability of each flash having attached within a 25 m radius around the location of Case A using *Huddleston* et al.*'s* and *Hunt* et al.*'s* method [38,39] as described earlier. Fig. 6b shows the results of applying this approach - probability against time. A single flash (detected at approximately 14:06:43 SAST), consisting of 4 strokes, is



(a) Tearing-and-tattering of trousers and socks.

(b) Rupture of the shoes.

(c) Scorching/singeing of the white drawstring.

(d) Singeing of pubic hair.

(e) Rupture of the left eardrum

(f) Pneumomediastinum

(g) Left petrous bone haemorrhage.

Fig. 5. Autopsy photographs for Case A.

the most likely flash responsible for Case A - having a probability of attaching in the 25 m radius significantly larger than any of the other reported flashes. Fig. 7 shows the reported locations of the 4 strokes that comprise this flash relative to the location of Case A, indicating the peak currents that were recorded for each stroke as well their 99% confidence ellipses and the strokes associated with the other flashes in the area.

4.1.5. *Voltage gradient estimation*

Fig. 8 shows a plot of the voltage gradient that would be developed between the feet of the victim for the 4 strokes attaching within a 10 m radius around the victim. It is important to note that this is an approximation relying on the homogeneity of the soil and assuming that current only flows close to the surface. This figure also does not consider the scenario that the electric cable was present, which would lead to a

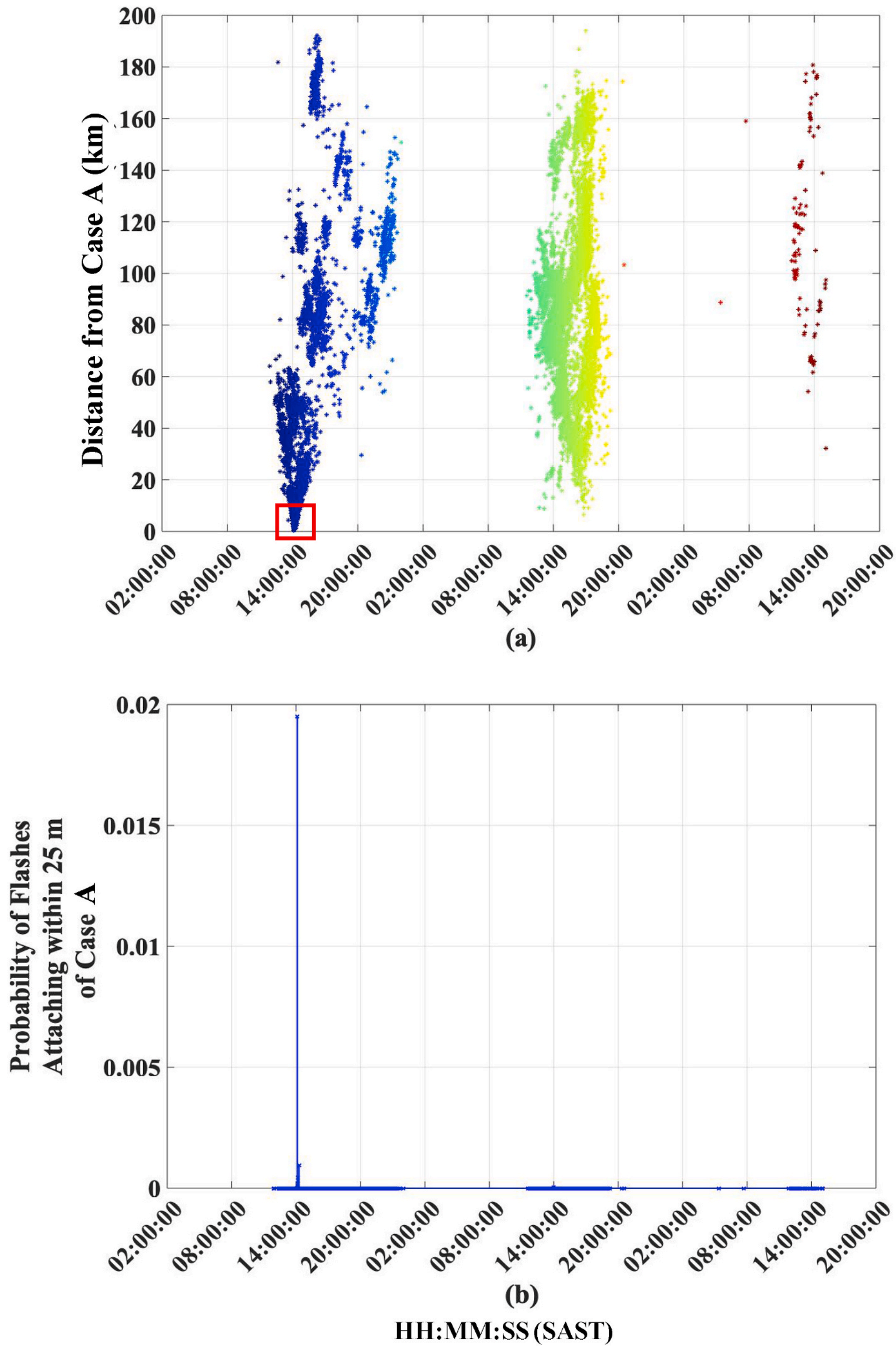


Fig. 6. South African Lightning Detection Network (SALDN) flash location reports for a weekend in February 2020 in the Gauteng area plotted as (a) distance from Case A location and (b) probability of flash attaching within a 25 m radius of Case A.

significantly more complex analysis.

A resistivity of 150 Ωm is used for the profile, based on the soil resistivity measurements from the site inspection. We can see from the figure that, given the peak currents of the strokes in the most likely flash, the voltages that would be developed between the victim's feet fall below 100 V after about 1 m and fall below 20 V after 10 m. If we estimate human body resistance at 1000 Ω, this indicates step potential currents of approximately 100–20 mA within 1–10 m. If we consider the 4% that could potentially flow through the heart, we have a range between 4 and 0.8 mA, very low current unlikely to cause death.

4.1.6. *Cause of death*

Analysis of the case leads us to conclude that lightning was indeed the cause of death. The eyewitness report combined with the features of the autopsy (torn and tattered clothing, ruptured eardrum, pneumomediastinum) and the SALDN report (and the presence of a identifiable flash with high probability of attaching within 25 m) make this the most likely explanation for the cause of death. Approximately 40–50 psi blast overpressure is required to rupture a 70 kg adult's tympanic membrane and therefore, the presence of pneumomediastinum indicates that the lightning flash likely attached very near (or to) the victim (possibly within 10 m) [44]. The fact that there was singeing of pubic hair tends to suggest direct open-flame effect of the lightning channel, highly

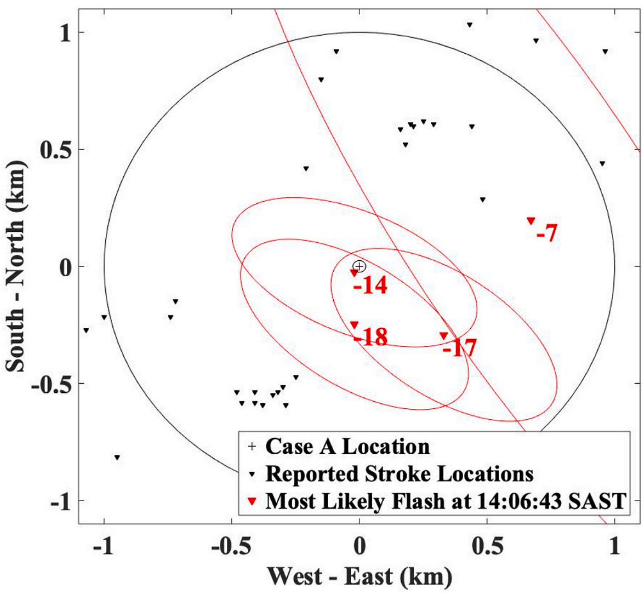


Fig. 7. Reported locations of SALDN detections in a 1 km area around Case A with the flash most likely to be responsible indicated. Peak currents and 99% confidence ellipses are also indicated.

suggestive of a direct strike (or one within very close proximity).

The lack of tall structures and objects nearby the victim make it very unlikely that the touch or side flash injury mechanisms occurred here. The voltage gradient estimation indicates that very low voltages would be developed between the legs of the victim (and therefore, very low current magnitudes through the heart) if the flash attached further than 10 m away. The presence of ruptured ear drums and of pneumomediastinum also indicate close proximity to the flash. This makes a scenario in which the flash attached to one of the light posts, and the victim was killed through the step potential mechanism, very unlikely. The lack of injury marks or exit and entry points on the skin and upper part of the body make confirmation of direct strike difficult, however, the singeing of the pubic hair and the tattered and torn clothes are less likely to occur if the upward streamer was the mechanism that occurred (could be present from step potential). A similar discussion can be found by *Anderson* et al. [45].

We cannot confirm the presence of a possible on surface cable at the scene as this relies solely on witness testimony, but if we consider the possibility that the cable was there, the scenario changes significantly. Firstly, the possibility of side flash or touch potential could be at play (if the victim was standing on/close to the cable and partial lightning currents flowed through the cable). Similarly, if this occurred, the voltage gradient in the soil would be significantly different and the possibility of much higher voltages being developed between the victim's feet could exist, meaning step potential could also be the mechanism of injury. As such, we are able to confirm lightning as the cause of death in Case A and that the flash was most likely a direct strike (if not, one in very close proximity to the victim).

4.2. *Case B*

4.2.1. *Case history*

An adult black female was found in a field in the Pretoria North/Tshwane region of Gauteng province in South Africa, on the Monday after a weekend in February 2020. The body was found on a path cutting through the field where the height of the grass had been reduced (likely from vehicles and foot traffic). It appears the deceased was walking through the field when the incident occurred. The event was unwitnessed and the initial investigation did not reveal when the incident occurred. According to the available history, she was last seen alive on the Saturday of the same weekend, which was two days before she was found dead.

4.2.2. *Site description*

The location where the body was found was an open field in a sparsely constructed area off of a main road. Fig. 9a shows an aerial view of the area. The location where the body was found is indicated and a 25 m radius around this location is shown. As can be seen, no structures, trees or any tall objects are within this radius with the only such objects being trees found over 50 m away. Fig. 9b shows a panoramic photograph of the field taken from the location where the body was found - clearly showing no tall structures/objects in the area. A photograph of where the deceased was found is also shown.

An analysis of the soil resistivity was conducted following the same procedures as described in above sections, and the results of the measurements are shown in Fig. 9c. The soil was noted to be soft and clearly with high moisture content. As can be seen, the measured soil resistivity in the area was much lower than 25 Ωm, ranging between 6 and 12 Ωm in depth. This indicates highly conductive soil, dissipating lightning currents well and leading to less step voltages being developed. The decrease from 1 m to 2 m is likely due to the surface of the area drying slightly as the storm in the area occurred a number of days before the measurements were taken.

4.2.3. *Autopsy report*

The deceased was an adult black female, showing signs of early putrefaction. No reliable visual facial identification could be made due to the decomposition. She was clothed in a long-sleeved woollen pink jersey (which showed no damage or injuries). She wore a short-sleeved synthetic yellow t-shirt, a skirt, a short length synthetic petticoat and synthetic underwear, a sneaker on the left foot and another sneaker lying separate from the body.

There was a star-shaped metallic church-affiliation broach on the left side of the pink jersey, which showed no signs of 'metalization'. The synthetic t-shirt and petticoat were singed (scorched-and-melted), chiefly overlying the left shoulder region, right upper aspect chest region

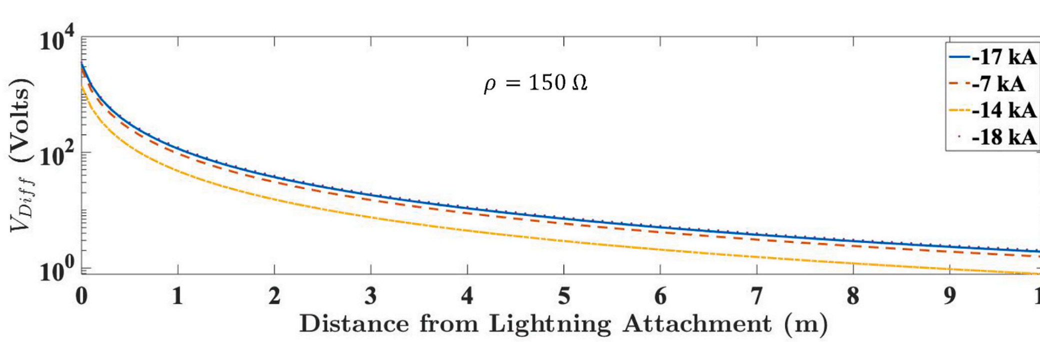
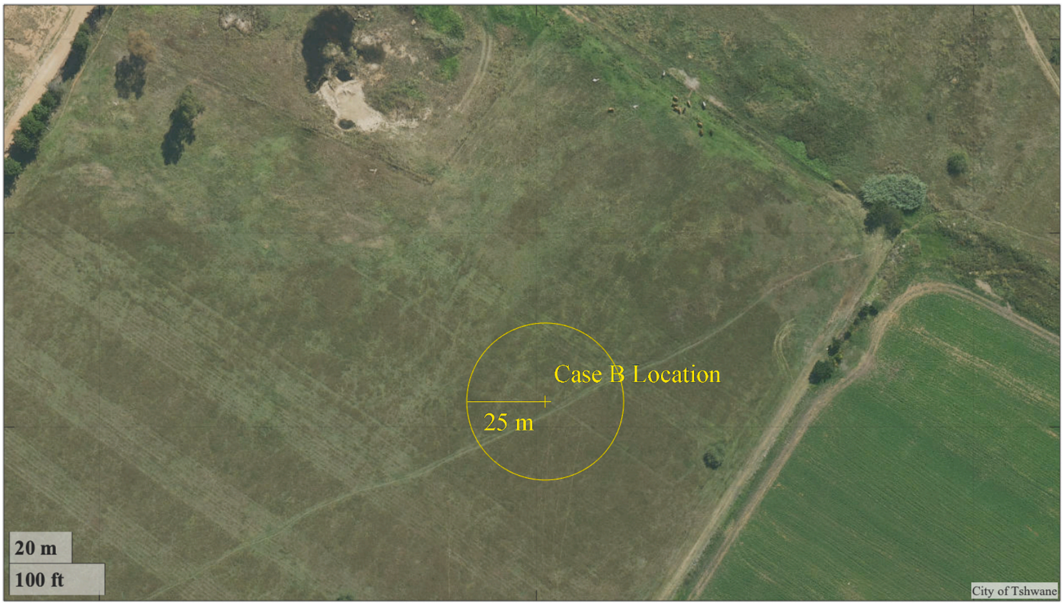
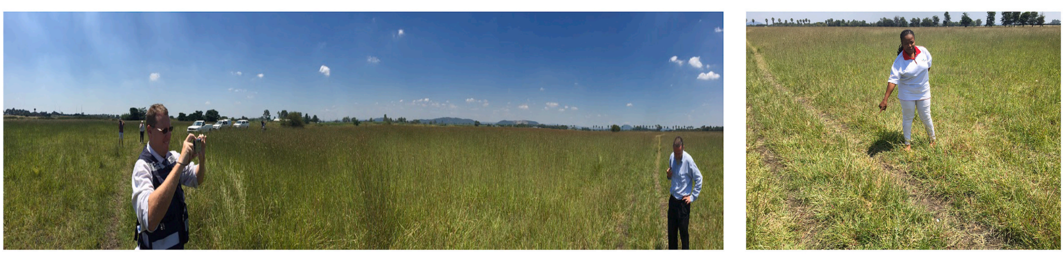


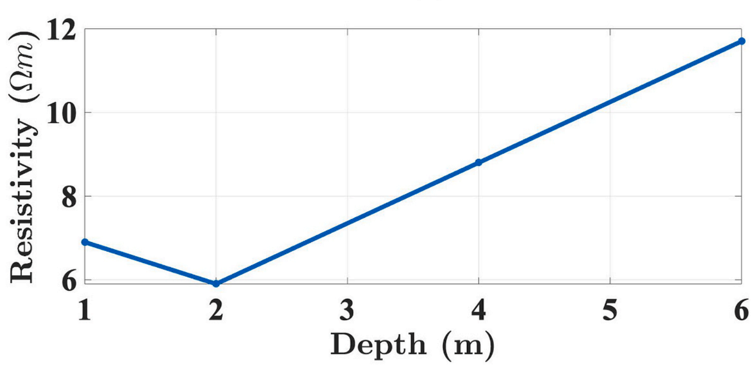
Fig. 8. The estimated voltage developed between the legs of the victim as a function of distance from lightning stroke attachment point, step length of 0.5 m.



(a)



(b)



(c)

Fig. 9. (a) Site location of Case B with a 25 m radius indicated. (b) Panoramic photograph of site location (note the open area with no tall structures in the vicinity) and the location where the body for Case B was found (c) Soil resistivity plot for the area.

(a) Tearing and scorching of the yellow t-shirts.

(b) Tearing and scorching of the yellow t-shirts.

(c) Rupture of the right shoe.

(d) Rupture of the right petticoat.

Fig. 10. Autopsy photographs for Case B.

and almost the entire back of the t-shirt (Fig. 10a and b). The sneakers had metallic zippers instead of laces and eyelets, which showed no abnormalities. The right sneaker was ruptured on the heel region and lateral aspect of the material (Fig. 10c). No rupture was found on the left sneaker. There was scorching of the left lateral side of the petticoat (Fig. 10d). Interestingly, the pink jersey and skirt were intact. There was some soot deposition on the back of the jersey and on the anterior and posterior aspect of the t-shirt (suggestive of open-flame, or heat effect). A red cotton traditional string was wrapped around the left wrist which showed no damage. A set of metallic keys were present in the palm of the hand which were attached to the string, which showed no damage.

The ears showed no rupture of tympanic membranes but external examination showed multiple small brown burn wounds (coagulated epidermis) with a charred centre and raised nodules on the edges on the lower half of the right side of the face. Several densely coagulated burn wounds with a targetoid appearance and charred centre were noted on the 1st web area on the dorsal aspect of the left hand. Internal organ examination proved non-specific, due to the relatively advanced stage of decomposition.

The chief findings were suggestive of a direct lightning strike: The synthetic t-shirt and petticoat were singed (scorched-and-melted), chiefly overlying the left shoulder region, right upper aspect chest region and almost the entire back of the t-shirt (Fig. 10a and b). There was soot deposition on the back of the jersey and on the anterior and posterior aspect of the t-shirt (suggestive of open-flame, or heat effect). The rupture of only the right sneaker is shown in Fig. 10c. There was scorching of the left lateral side of the petticoat (Fig. 10d). The findings on the left hand and right side of the face were suggestive of electrothermal-type injuries. As such, we are able to confirm lightning as the cause of death in Case B and that the flash was suggestive of a direct strike.

4.2.4. *Lightning location system report*

Fig. 11a shows the lightning flashes detected by the SALDN. The plot now shows the data as a function of distance from the location of Case B. We again see the three distinct thunderstorms that occurred on the Friday, Saturday and Sunday of the weekend in February 2020 (blue, green/yellow and red respectively). However, in this case we see that the storm that occurred on both the Friday and Saturday passed over the location of Case B, with many flashes reported by SALDN close to the location. Unlike Fig. 6a in the previous case, it is unclear from this plot whether the responsible lightning event (and therefore the time of death) occurred on the Friday or the Saturday of the weekend in February 2020.

We again apply the methodologies of *Huddleston* et al. and *Hunt* et al. to calculate the probability that each detected flash attached within a 25 m radius of the location of Case B [38,39]. Fig. 11b shows the probability against time plot and it becomes clear which flash is responsible - a flash consisting of a single detected stroke occurring on Saturday at approximately 17:23:53 SAST. Fig. 12 shows the reported location of the stroke relative to the location of Case B, with a peak current of −14 kA and 99% confidence ellipses indicated.

4.2.5. *Voltage gradient estimation*

Fig. 13 shows a plot of the voltage gradient that would be developed between the victim's feet for a lightning stroke with peak current of −14 kA attaching within a 10 m radius around the location of the deceased. The higher resistivity value is chosen (12 Ωm) as the worst case measurement. From the estimation, we can see that the voltage developed is already less than 100 V within 1 m and this is due to the high

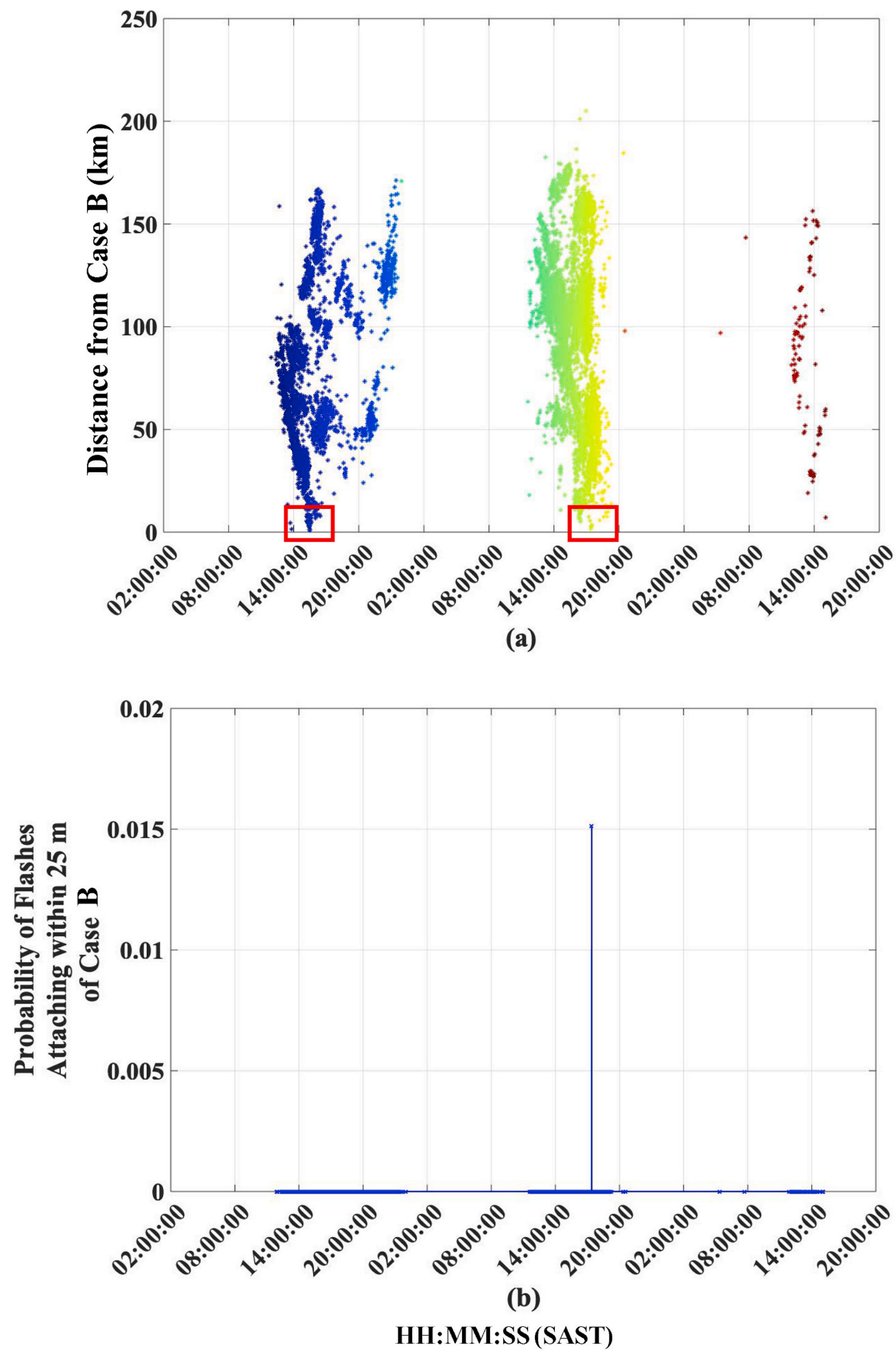


Fig. 11. South African Lightning Detection Network (SALDN) flash location reports for a weekend in February 2020 in the area plotted as (a) distance from Case B location and (b) probability of flash attaching within a 25 m radius of Case B against time.

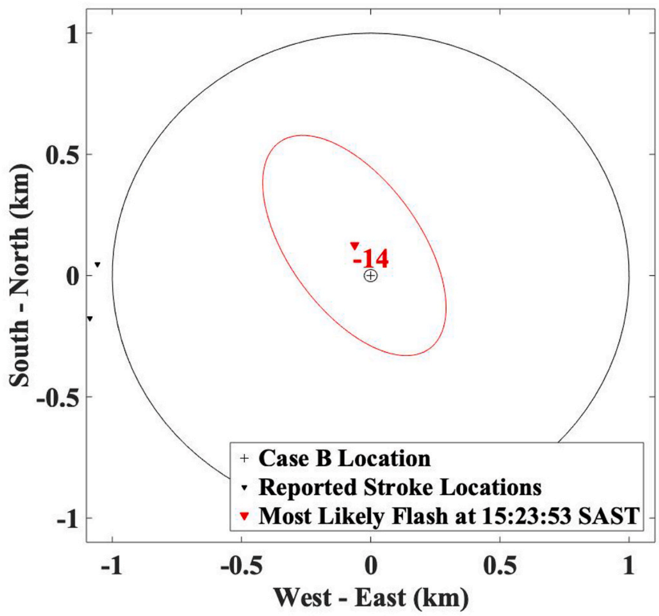


Fig. 12. Reported locations of SALDN detections in a 1 km area around Case B with the most likely flash indicated. Peak currents and 99% confidence ellipses are also indicated.

conductivity of the soil in the region. Over 10 m, the voltage that would be developed is close to zero.

The closest tall object in the area (tree) is more than 50 m away. If the tree was struck, the voltage developed between the victim's legs would be so close to zero the step potential mechanism could not be considered. Estimated currents that could flow through the heart would be in the range of 4–0.1 mA.

4.2.6. Cause of death

Analysis of the case leads us to conclude that lightning was again the cause of death. The features of the autopsy (scorched and melted shirts, soot deposition on the jersey, ruptured single shoe, small burn wounds on face and left hand) and the SALDN report (a the presence of a identifiable flash with high probability of attaching within 25 m) make this the most likely explanation for the cause of death.

The open area with no tall structures/trees/objects near the location of the deceased lead us to exclude touch potential and side flash injury mechanisms. The low soil resistivity values allow us to estimate the voltage profile based on the −14 kA stroke peak current identified in the SALDN data, and these indicate that the soil is much too conductive to consider step potential as the injury mechanism. The burning of the clothes and the small burn wounds seen on the face and left hand indicate some degree of electro-thermal activity very unlikely to occur during the (comparatively) low charge flow seen during the upward streamer mechanism. This led us to conclude that the cause of death in Case B was most likely due to direct lightning strike.

5. Lightning safety issues

The analysis of the two incidents reveals two important safety issues common to South Africa, and likely to many African countries as well.

1. The victims in both incidents walked along an open path with low surrounding growth (or no-growth). Thus, the victims have made themselves a prime target for direct strike and also have a high exposure to step potential in the event of a nearby strike. As per the facts extracted from the interviews, there apparently was no urgency for the victims to seek shelter, disregarding the overcast/storm conditions at the time. Such action by the victims may be the result of either the lack of awareness of the risk of being exposed or the negligence/ignorance of the known safety procedures. Both could be categorized as the lack of lightning safety education.
2. The other point is more technical than social - a casual investigation on the small dwellings in the area, especially the respective structures, which the victims have occupied before they moved out, reveals that none of them could be treated as safety shelters. Almost all of these structures are metal roofed with wooden or clay walls. In the event of a lightning strike to such structures, multiple casualties could result, as per the observations reported in the previous literature on the incidents in Africa [22,46]. Such situations raise the question of whether it is fruitful to increase the lightning safety awareness among the people in such communities, without providing them sufficient safety measures.
Hence, this study highlights the dire need of urgently addressing the above issues, by both governmental and non-governmental organizations, in many countries with high lightning ground flash density, especially those in Southern Africa. Adopting or providing lightning safety measures in any developing country remains a challenge and has never been convenient. When looking at avoidable factors, both deaths could probably have been prevented by staying indoors. Practicing lightning safety does not require significant funding. Enhancement of public awareness on lightning safety guidelines and providing lightning safety measures should be done simultaneously. Considering the large population that requires such protection measures, it is almost impossible to provide comprehensive protection to all vulnerable structures in the region. Therefore, out of the box solutions are required where the protection measures proposed are affordable to the public and also to the donors. Thus, it is recommended that low cost solutions proposed in the recent past should seriously be considered by the relevant authorities to be implemented in mass scale [22,47]. A lightning safety community model suitable for underprivileged communities should be adopted at governmental level [48], rather than having an isolated approach to solve this issue.

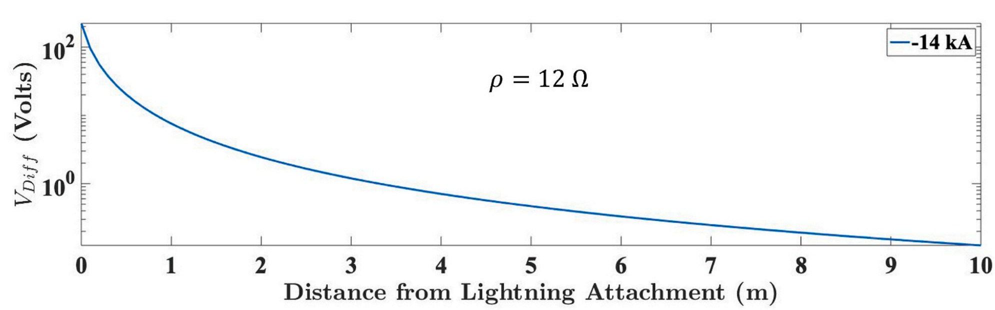


Fig. 13. The estimated voltage developed between the legs of the victim as a function of distance from lightning stroke attachment point, step length of 0.5 m.

6. Conclusion

This paper presents the findings of a multidisciplinary forensic investigation of two lightning related deaths that occurred on a weekend in February 2020, in the Pretoria region of South Africa. For both cases, lightning was confirmed as the cause of death. In the first case, the event had eyewitnesses and the lightning location system data and analysis confirmed the presence of a storm as well as a flash consisting of 4 strokes and high probability of being responsible. The medical autopsy indicated that the event must have been in close proximity to the victim (if not a direct strike) due to the ruptured eardrums. The voltage gradient analysis ruled out the possibility of lightning attaching to a nearby light post and causing death through the step potential mechanism indicating again that, if not a direct strike, then the event must have been very close to the victim (within 10 m). The second case was unwitnessed but the lighnting location system data analysis again confirmed storm activity and likely flash (consisting of one stroke) could be identified. The autopsy indicated direct strike (the clothing examination) as the mechanism and the voltage gradient analysis ruled out the step potential mechanism (due to the very conductive soil in the area), leading to the conclusion that direct strike was the mechanism of death. Both cases indicate an issue with lightning safety awareness and the risk of exposure in rural African contexts.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2020.101814.

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