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A STUDY OF EARTH POTENTIAL RISE SHOCK in LIGHTNING INJURY

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Abstract - The operation of EPR both indoor and outdoor is presented in a classical analysis, and then attention is drawn to non-ideal features as presented by Kitagawa and colleagues. The danger of EPR for VF for individuals in the open is shown to be operative only close to a lightning strike, and that when EPR danger exists, a victim is much more likely to receive a direct strike.

Upward streamer shocks are considered to be more numerous than previously considered, and constitute an under-recognised mechanism of injury.

Possible inexpensive strategies to minimise EPR shock, especially indoors, are given. These include use of footwear including flip/flops, use of matting, sleeping above a ground plane, and the use of multi-layer earth structures. These are considered as simple, practical, and inexpensive.

Keywords – EPR, Earth Potential Rise, Upward Streamer, Lightning Shock, Striking Distance

I. INTRODUCTION

This study was stimulated by discussions with colleagues from the ACLEnet project[8]. This project fosters, among other things, protection of African schools, and people, from injury by lightning. The paradigms of such a project are different from applying protection in a western affluent society. Among questions asked are how beneficial might it be to institute very simple and inexpensive protection strategies, with somewhat decreased protection efficacy, but still representing valuable partial protection for limited outlay. Central to answering this question is knowledge of Earth Potential Rise shock.

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Shock by earth potential rise is one of five mechanisms by which a lightning stroke can affect an individual. Three of the mechanisms are:

a. *Direct strike,* where a person is the sole attachment point for a lightning return stroke in the field.

b. *Contact potential*, where a person is in physical contact with an object that is struck and forms a parallel path for lightning current to pass to ground.

c. *Side flash*, where a person stands close to an object that is struck, e.g. a tree, and the air between the object and the victim breaks down and a current flash “jumps” to the victim from the object. In both (b) and (c) the current divides between the object and victim in inverse proportion to their impedance.

In the past, the author has seen circumstances arise, (e.g. at a sports match) where an individual appears to be struck, and other members of the team in the playing field, often many metres away, have collapsed, possibly unconscious, but were not directly struck. A fourth mechanism could be active:

d. *Earth Potential Rise (EPR) shock*. EPR shock, also known as Ground Potential Shock, or Step Potential shock, occurs when current is injected into the earth, and travels away from the injection point. Earth has a finite, and variable, resistance, and current travelling through this resistance generates electrical potential. Body parts in contact with earth at different points will be subject to a potential difference, and the body will experience a current flowing between those points. The points on the body have a finite and broadly known impedance between them, and form current division paths.

A fifth mechanism has been documented which may be an equally likely explanation for this phenomenon[1, 2, 5, 9, 10]:

e. *Upward Streamer Shock (USS)*. In this mechanism, a current “leader” makes angled passage from a cloud toward ground.

> Many objects at ground level, proportional to their height size and angular projections, initiate upward induced leaders which develop to meet the downward leader. If the upward leader meets the downgoing leader, a path is completed and the attachment becomes a direct strike. In the process of developing an upward leader from a person, current is transmitted from the ground through the victim to form the leader, and this may be injurious despite attachment not occurring. Similarly, if the upward leader collapses unsatisfied, the collapsing current through a person may be injurious. The magnitudes of current in USS have been quantified[4, 3].

It may be that upward streamer shock is more common than has been thought, vide infra. The circumstances where individuals have collapsed quite distant from the primary stroke have been rather glibly attributed to EPR shock in the past, and it may be quite difficult to separate the mechanisms for any individual affected by any one strike, and especially EPR versus USS. In a group of victims, for example, multiple methods may operate simultaneously.

One question which arises is the distribution of morbidity and mortality versus the mechanism above. The first part of answering this question is to determine what percentage of all victims are subject to each particular mechanism. This distribution is conjectural as there is no reliable means of determining this objectively. The reasons for this have been given[11]. Estimates vary and Table 1 shows an accepted distribution[11], noting that this is not mortality, but incidence, for each mechanism.

TABLE I. A DISTRIBUTION OF LIGHTNING INJURY MECHANISMS

Direct Strike	3-5%
Contact Potential	3-5%
Side Flash	30-35%
EPR	50%
USS	10-15%

The second part of the question requires an estimation of the mortality rate for each mechanism. There is no literature on this question. Intuitively one might consider Direct Strike to be the most fatal, but there is no data or study supporting this conjecture. Thus the mortality for each mechanism requires research, if it can be determined at all.

II. Initial Considerations - Outside and Inside cases

This paper initially considers the classical idealised theory for EPR. The theory is then modified in the light of closer consideration, particularly reported by Kitagawa and colleagues[14, 15].

This paper examines two distinct circumstances.

The first is the situation where victims are standing in-the-field and asks the question, “Can an EPR exposure generate enough current to be injurious?”. A 50th percentile strike of 35kA, is considered, and the victim is an entirely unprotected individual standing in the open (Fig 1). Injection of current to earth can occur in different ways -If an object is struck – a building or tree, etc – current is injected at the base of the object to earth. Similarly, a lightning flash can inject directly to earth. The EPR generated is examined.

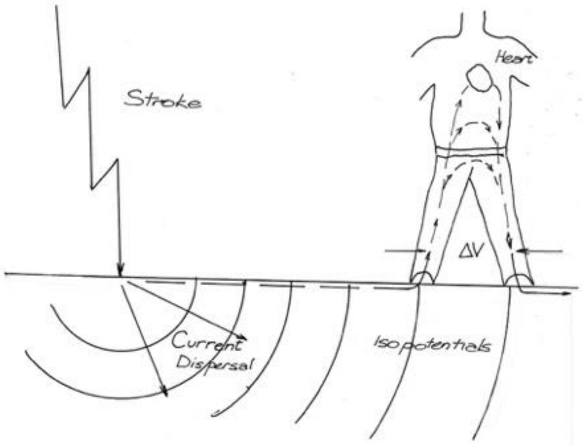


Figure 1. Classical EPR Schema

The second circumstance of interest is where EPR can affect people inside inadequate (from a lightning protection viewpoint) structures. An example is inside a tent near one or more struck tentpoles[5] (Fig 2). A strike to a tent pole will inject current to its base, and EPR will occur around the base into the earthen interior. Those at risk may include individuals sleeping on the earthen floor. A similar situation will be seen with an ungrounded metal roof, supported in a type of A-frame structure with supporting posts dug into earth. Current from a strike to the roof may be transmitted down supporting poles (Fig 3), and an EPR field will be set up, including inside the building.

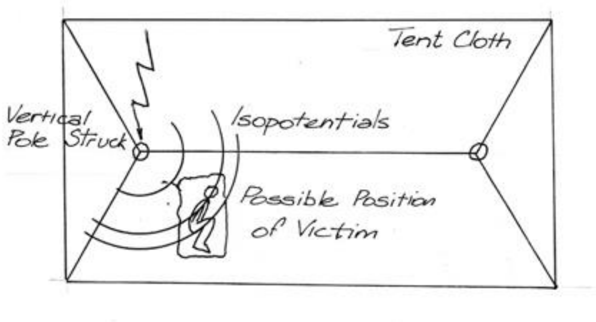


Figure 2. Tent Plan (after Carte[5])

Consideration of this second circumstance is from an EPR viewpoint only. Certainly, side flash or contact potentials may equally cause injury. The place of USS inside a building is conjectural. The effect may be small given only partial lightning current being involved and the distances being short. Similarly furniture, like the metal legs of a table in an EPR field, may give rise to side flash or contact potential.

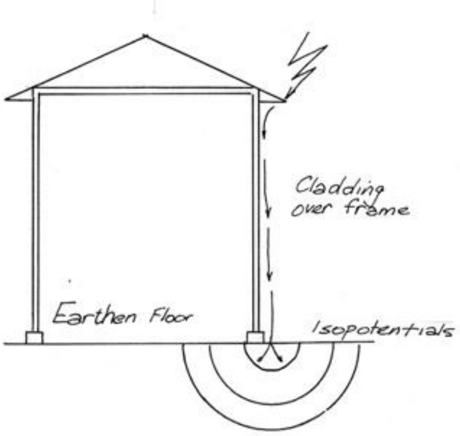


Figure 3. Building with bare earth flooring

We consider the outside case first. In an EPR field what potential difference must exist between the feet to cause a dangerous current to flow? Given the foot-foot pathway, the only threshold available to us is to consider the risk of ventricular fibrillation (VF) from current injected in this way.

Figure 1 shows the classic configuration for humans. A human stands in the potential field of the injection point. A potential difference between their feet causes a current to flow via the legs. The existence of parallel paths tells us that cardiac current occurs, albeit at a low level. The Standard IEC60479-2 [7] shows that a current transmitted *hand to foot* and 1ms in duration has a 50% risk of VF if the current is greater than 5000mA (5A), based on a 5mC charge threshold. The heart current factor (F) is 0.04, and so the current needed in the *foot-foo*t path for a **50% risk** of VF is approximately 125A. An estimate for the foot-foot impedance is (based on large areas of dry contact) 750 ohms [6], and so the potential required for this current becomes 93kV. For the lowest threshold of VF risk **(<1%)**, the potential found by similar means is 18 kV. The length 1mA is chosen to account for multiple strokes in a flash and any continuing current.

Thus a large potential is needed to cause VF via a *foot-foot* path, being at least 18kV, for a 1% chance of VF. We will examine whether this threshold can be met for feet 1 m apart, and under what circumstances, below. It should be noted that this considers VF risk only, and there is no known threshold otherwise for lightning injuries, either physical or psychological.

III. THE CLASSICAL THEORY

We now develop the idealised classical theory and then modify it from ideal.

1) *First Case*

The classical theory is shown in Fig 1. A current **I** is injected into a ground of resistivity **ρ.** The current is assumed to flow evenly in all directions in a soil of uniform resistivity. At a distance **r** from the injection point, for a hemisphere, the current density **J** is

$$\boldsymbol{J} = \frac{\boldsymbol{I}}{\boldsymbol{2\,\pi r^2}}$$

The electric field **E** at **r** is

$$\boldsymbol{E} = \boldsymbol{J\rho}$$

$$= \frac{\boldsymbol{I\rho}}{\boldsymbol{2\pi}}\ \frac{\boldsymbol{1}}{\boldsymbol{r^2}}$$

Given that electrical field is the gradient of electrical potential, that is potential is the integral of field, the potential distribution around the strike base is made up of concentric circles with isopotentials dependent on **r**.

$$\boldsymbol{V} = -\frac{\boldsymbol{I\rho}}{\boldsymbol{2\pi}}\ \frac{\boldsymbol{1}}{\boldsymbol{r}}$$

If we now take a potential difference between two points, **r₁** and **r₂**, 1m apart, we obtain, (neglecting the sign which is of no moment),

$$\Delta\boldsymbol{V} = \frac{\boldsymbol{I\rho}}{\boldsymbol{2\pi}}\left(\frac{\boldsymbol{1}}{r_1} - \frac{\boldsymbol{1}}{r_2}\right)$$

where r_2 - r_1=1, or r_2 = 1 + r_1(i.e. **r₁** the nearest point to the strike)

And thus,

$$\Delta\boldsymbol{V} = \frac{\boldsymbol{I\rho}}{\boldsymbol{2\pi}}\left(\frac{\boldsymbol{1}}{r_1(1+r_1)}\right)$$

where **r₁** is the distance of the nearest point to the strike

This may be shown graphically (Fig 4) where I=35 kA Representative values of soil resistivity are given as per Table 2.

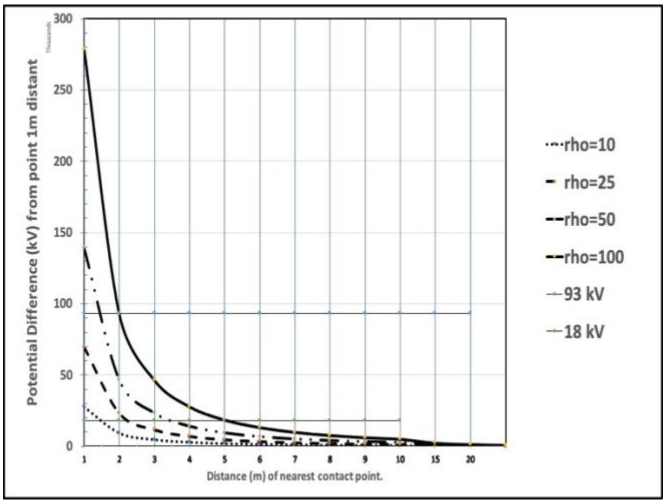


Figure 4. Potential Difference for points 1m apart [kV] vs distance [m] from stroke (scale change at 10m)

Figure 4 shows representative values for resistivity of 10-100 Ωm. These are the majority of important commonly occurring soils. It will be noted that for a person standing on two feet, the VF threshold of 18kV is exceeded only if a person is no more distant from the strike than approximately 5m from the base of the stroke.

TABLE II. **Resistivity Values** (derived in part from Australian Standard AS1768)

SOIL	Resistivity Ωm
Damp Clay	10
River Bank Alluvium	25
Clay Sand Mixture	30
Dry inland soil	100
Concrete 1 part cement, 3 parts sand	150 (avge) – range (50-300)†
Concrete 1 part cement, 5 parts gravel	400 (100-8000)†
Sand	3000
Rock	20000

† metal reinforcing may decrease these values

However an important consideration is that the striking distance d_s for a stroke is given by

$$d_s = 10 \times I^{0.65}$$

where I is in kA [21]

For a 35000A stroke, d_s is 10.0843m. The implication is that if standing at a distance from a stroke base which would make EPR potential a VF risk, then a victim is at extreme risk of becoming the attachment point for a direct strike. Thus injury risk is more likely from a direct strike than EPR.

An alternative way of examining the equations is to solve for r_{1max}, the maximum distance inside which a victim is exposed to higher than the threshold risk of EPR for VF.

These are (see also Fig 4, taking the highest soil resistivity, noting that for lower resistivities the distance is much shorter.):

Potential Difference kV	Maximum distance (m) below which this value is exceeded
93 (50% risk)	1.99 m
18 (1% risk)	5.08 m

All of these are inside the striking distance (10 m), thus for a person in the open and standing, EPR contains minimal risk compared with direct strike. Alternatively, at the maximum distance for which VF risk exists, a direct strike is more likely. If outside these required distances, USS is more likely to be operative than EPR, and thus it may be that USS has been undervalued in favour of EPR shock in the past.

2) *Second case*

We consider now the case of an individual inside a structure. This may be within a tent near a tent pole,[1, 2, 5], (Fig 2), or perhaps an inadequately shielded building (Fig 3.).

We consider an individual child lying on earth in a tent. Contacts are considered to be shoulder and hip. The impedance of this pathway is estimated from IEC60479-1 [6]. Using Figure 2, the impedance is approximately 30% of the total hand-foot impedance. Discounting the total for a child to 850 Ω, the impedance shoulder to hip is estimated as 255 Ω. The distance shoulder to hip is estimated as 46cm extrapolating from published data [16]. The heart current factor for this pathway is approximately 0.7, giving a VF threshold of 2100 mA (1%) and 3500 mA (50%) ([7] Figure 23) for VF. To achieve this current, the applied voltages need to be 535 V (1%) and 893 V (50%).

These voltages are obviously easily achieved if a tent pole carries the full brunt of the 35 kA lightning impulse, and easily achieved even if only a small fraction of the main impulse transits a particular pole.

Of course, the possibility of side flash from the pole also exists rather than EPR. Direct Strike inside a structure is not considered as it is unlikely, however if one considers side flash, USS in the development of a side flash may well operate.

The overall conclusion for humans outside in the EPR field, based on this idealised analysis, is that EPR poses little risk of VF compared with the striking distance, and EPR injury is much less likely than a direct strike. There are however no criteria for *injury* prediction. In the open, provided a victim stays outside the striking distance of 10 m where EPR poses no risk of VF, there must be other mechanisms to account for injury other than EPR. It may be that USS is responsible for significantly more morbidity than EPR than previously considered, and this is consistent with the first observation of players at one end of a field being affected when there is a strike at the opposite end.

EPR would seem to be significant indoors however. For the child lying, only a small current conducted down a tentpole would seem to be necessary to set up an EPR field of danger. The situation is complex especially for those not lying. Side flash may be significant, especially near supporting posts as might contact potential, and the place of streamer shock in these. Metal formed furniture may well carry significant current if its feet are in an EPR field, and generate side flash and/or contact potential. However for a person standing indoors, the risks of an EPR field revert to values similar to an outside field. If a post carries the brunt of an impulse, the distances previously calculated will hold. The likelihood of side flash or contact potential perhaps become more significant. The interplay of remaining mechanisms is complex.

IV. KITAGAWA'S APPRAISAL

The above analysis is idealised. It assumes a constant earth resistivity, with a current completely contained within the earth structure, which is assumed flat and homogeneous. This is an idealisation and rarely approached in practice, particularly with outdoor activity on mountains.

It does not allow for inevitable earth irregularities, leading to arcing within the earth substance[22]. It does not allow for the **E** field on the surface to exceed flashover limits, and for surface arcs to develop. Further it does not allow for imperfections in the surface, over which breakdown in air may take place. Surface imperfection is shown in Fig 5, after Kitagawa[14, 15], for example, which shows a pathway, derived from EPR, where the pathway is not just purely foot-foot. This path is a high risk for VF derived from EPR.

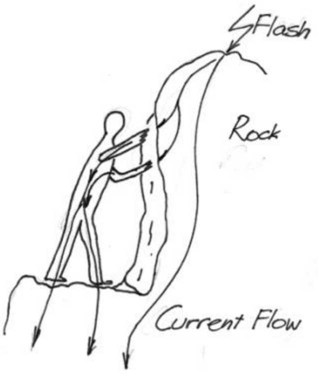
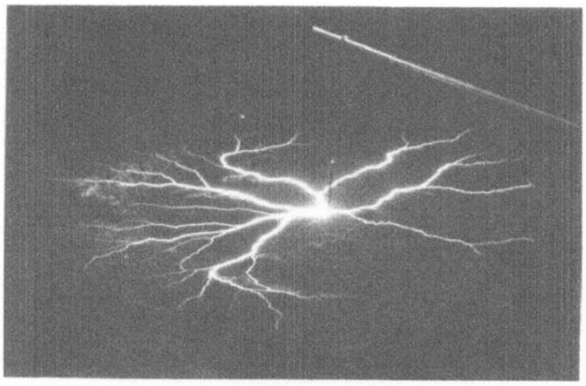


Figure 5. Step Voltage (non idealised), after Kitagawa [14, 15]

Kitagawa provides an appraisal of practical EPR behaviour[14, 15] He suggests two factors making the classic theory an over-simplification, and those are that most injected current is conducted in the surface layers of the earth, which is not homogeneous, and secondly that surface breakdown occurs.

In the second case, the surface field may exceed the breakdown strength of air over a surface. He states that this is near 500kV/m, and may be as low as 250kV/m over a wet surface. This field is exceeded up to approximately 2m from the strike base. When the surface field is exceeded, breakdown occurs giving surface arcs, and less current flows in the ground. If more current flows in the surface layers, the breakdown field is likely to be exceeded for a larger distance from the strike base.

The consequence is that surface breakdown arc will also constitute danger for a person standing in the open. Fig 6 shows an example of surface flashover[22], across wet soil. Indeed arc tongues may extend for several metres from the base of a strike, but yet seem to remain within the striking distance. Thus danger from surface arcing increases the danger of a fatality occurring outside, and still direct strike remains a real risk.



Surface arcs from the top of a driven rod caused by a lightning impulse current of about 15 kA into loamy sand wet by rain sprays [redacted]

Figure 6. Surface discharge, after Wang et al. [22]

Kitagawa states that the inaccuracies mentioned are not possible to predict analytically, and so the effect of EPR shock must be determined by empirical study. He documents multiple cases where groups of people are injured, said to be by earth potential rise, but he states these are more likely via surface arcing, which this author believes may equate to a mechanism somewhere between side flash and EPR. Fig 7 shows an example of a dangerous combination of these.

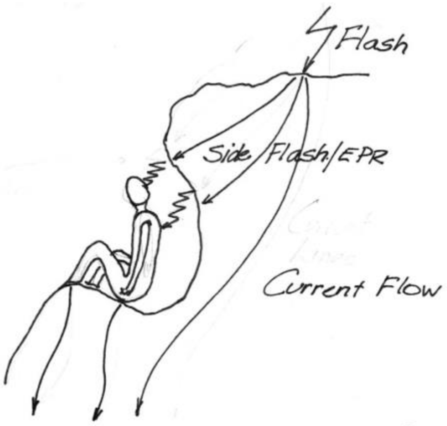


Figure 7. Combination Shocks after Kitagawa [14, 15]

V. DECREASING EPR RISK

Various methods have been proposed to decrease EPR risk. These are set out as bring simple and inexpensive in a third world environment.

a) Layered earth

The construction of earth in layers can mediate EPR effects. It may be possible to place a high resistivity layer of material as a layer over the standard earth. The layering of the earth in this way has the property of decreasing the apparent earth resistivity. Thus the danger of fatal shock is decreased.

The theory of layered earth is complex [13, 17-20].

Consider a two layered earth structure, with ρ_c being the resistivity of the surface layer and ρ_s being the lower layer. The quantity K is

$$K = \frac{\rho_s - \rho_c}{\rho_s + \rho_c}$$

We will propose a high resistivity surface layer lying over a lower resistance soil layer. K will therefore be negative.

On a single layer earth of ρ_s before the addition of the upper ρ_c layer, the resistance to a foot model is [17]

$$R_f = \frac{\rho_s}{4b} \ \Omega$$

where ρ_s is the resistivity of the single earth layer and b is the equivalent radius of a foot model.

Lin derives a formula for the resistance of a foot standing on a two layer structure, ρ_c ρ_s being as above, which becomes

$$R_f = \frac{\rho_c}{4b} \ H(x)$$

Where

$$H(x) = 1 + \frac{4}{\pi}\sum_{n=1}^{\infty} P$$

and

$$P = \frac{K^n}{2nx}\left[1 - \frac{7}{12}\frac{1}{(2nx)^2} + \frac{33}{40}\frac{1}{(2nx)^4}\right],$$

(x=h/b, h being the thickness of the upper layer)

K is negative in the circumstances described, P turns out to be positive, as does H(x).

The relationship between H(x) and h, is shown in Fig 8. Thus the resistance of a foot placed on a two layer ground, is greater than that of a foot placed on a single layer ground. For example, a 7:1 ratio of resistivity, K =-6/8, and if a 15cm high resistivity layer is used, the value of H(x) is just over 0.8, since ρ_c is significantly greater than ρ_s. Thus the resistance of a foot over a two layer earth is greater than that of the single layer earth by ρ_c/ρ_s times H(x) - in the case quoted, by a factor of 0.8 *7, equaling 5.6 times.

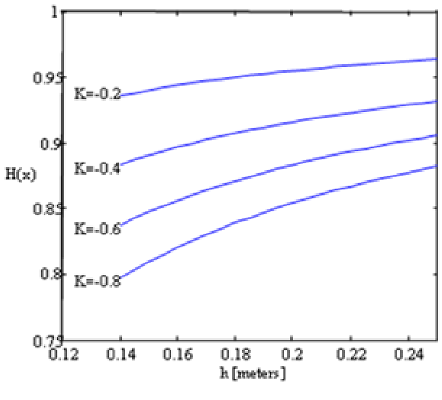


Figure 8. Relation between h and H(x), Lin [17]

Thus a two layer earth is a distinct advantage in reducing the injuring potential difference.

b) Footwear

Darveniza conducted an ad-hoc examination of the use of footwear under lightning stress[12]. He subjected himself to lightning shocks applied to one hand, while standing on earthed flooring in normal footwear. He found that up to 30 kV, the shocks were only mildly painful or discomforting, though above perception level. In a second test, while sweaty, with moist shoes in poor condition, the shock up to the same level was 'more severe" and accompanied by pain in the foot. It was found that this was due to a 2cm hole in the sole of the shoe giving direct contact with earth. Under the same conditions, sound shoes reverted to the previous mild reaction. These were hand-foot shocks, with the foot earth contact being capacitive. The current estimates were shown to be below VF thresholds. The impulse strength of footwear was approximately 34 kV (variably depending on shoe condition and manufacture. This threshold was predicated on hand-foot shocks and applying the cardiac F factor of .04, the implication is that up to 750 kV between feet with footwear is safe, provided the shoes were in good condition, and that the energy provided by the source was less than 5 J, the amount used in the experiments, and hence a specific current limit. He concluded that injury from foot contact will only occur if a surface arc reaches the victim. Fully enclosed footwear would seem to fulfil this requirement, compared with flip/flops. With persons who have never work shoes, thick keratin will devlop on the soles of the feet. This will provide increased resistance and therefore partial protection against EPR. However as the keratin does not extend to the sides of the feet, keratinisation is unlikekly to provide protection from ground arcs.

The implication is that footwear adds a degree of protection, such that the voltage drop across the footwear is less than 34 kV per foot. The victim starts off therefore with a 68 kV "advantage".

c) Intervening insulation.

Should a layer of 1 m^2 be interposed between a lying victim and the earth, additional resistance will impede current flow. If we consider a 1 m x 1 m square of rubber, 1cm thick, of approximate resistivity 10^{13} Ωm, its resistance will be 10^{11} Ω. This is a very substantial value reducing injuring current.

The use of flip/flops will offer some protection, diminished by fringing effects. If surface arcs exist, they may offer no real protection at all, though useful for indoor EPR.

VI. Discussion.

The first is the situation of interest is where victims are in-the-field. The question arises as to whether this victim is at risk from EPR shock. In the potential field generated by a 50th percentile strike of 35 kA, it is surprising that current will only reach a severe threshold for VF when the victim is quite close to a grounded strike. Within the distance required for harm from an EPR shock, the victim is well within the striking distance of the descending leader. A person close enough to a strike to consider danger from an EPR strike, is more at danger from a direct strike. Footwear will provide some protection from any EPR element unless there are surface arcs, but unlikely to do so for a high energy direct stroke. Further, if the victim is close enough to a struck object to suffer EPR injury, they are then more likely to be at risk of a side flash.

In the circumstance referred to, where a person at one end of a sports field is struck, and several other players “drop” a large number of metres away, say more than 50 m away, EPR cannot be active. Some suffer long term injury, physical and psychological. The author is of the view that we have misattributed the mechanism of these to EPR, when they are more likely to be due to USS. More widely, upward streamer injuries have been underestimated compared with EPR injuries.

The discussion above is predicated on VF risk, when working out relation to thresholds. There is no reliable threshold for injuries of other kinds, physical or psychological.

Given this discussion, this writer would reassess the proportion of significant injury to each method of contact. In a purely conjectural manner, Table 3 offers a subjective reassessment.

TABLE III. REASSESSMENT OF THE DISTRIBUTION OF LIGHTNING INJURY MECHANISMS

Direct Strike	5%
Contact Potential	5%
Side Flash	35%
EPR*	20%
USS*	25%

*Or even more in favour of USS

The second circumstance of interest is where EPR can affect people in inadequate (from a lightning protection viewpoint) structures. An example is the tent and tentpole above. A second example might be a building with vertical support poles to a roof, and an earthen floor. A strike to a support pole will inject current to its base, and EPR will occur around the base into the earthen interior. This will constitute risk to a standing victim on the same basis as in the field. However if a subject is lying on bare earth, they are at substantial risk from EPR shock. A complex of side flash, and contact potential also places all these at risk.

EPR risk will be ameliorated if a person does not sleep on the earthen floor, and sleeps on a raised bed with insulating, say wooden, legs. Such bedding could be inexpensive. Alternatively, a rubber mat on the earthen floor will also constitute EPR protection. The question remains as to how far such a mat should extend around an individual. Given a surface breakdown strength of 500kV/m over a rubber mat, and a very approximate voltage differential at points 1 m apart of much less than 300kV (a 35 kA stroke, in the open gives about 250 kV at 1m from the stroke) 1 m total mat width around a possible victim seems conservative. This ameliorates an arc across the mat. The mat, provided it is in good condition, will add substantial resistance to any other path through the victim from the earth, and may well be lifesaving.

Side flash and contact potential are difficult to quantify, so persons indoors should be distant from any structure (tent pole, vertical support) which could give a side flash. The place of USS in a side flash no doubt exists, and is also not quantifiable.

VII. APPLICATION.

The analysis in this paper was stimulated by a colleague who is active in protection strategies in developing countries. As with all philanthropic endeavours, finances are stringent, and the question was asked if were there simple and relatively inexpensive measures that could be adopted, to provide significant protection, which while perhaps not perfect, were significant. This study supports such simple strategies.

The usual attention to weather outlook should be given, though it may be that radio services may not be available in developing countries. A cheap radio nonetheless, if a broadcast station is available, for a community, might be a useful item. Social acceptability of radio broadcasts and radio function must also be taken into account.

Figure 3 shows a cross section of a vulnerable structure, as this is often contrary to western notions of a protected indoors.

At present, excellent protection is being built around Franklin rods and down conductors for schools. Coupled with this and especially for less developed buildings still having earthen floors, a compacted surface high resistivity layer like rock composite in appropriate places is helpful. Inside a building, a layer of high resistivity cover over a possibly low resistance floor, perhaps like compacted decomposed granite, might be considered. Rocky, gravel-like, cover is often recommended for substations, however utility must be considered for flooring in occupied spaces.

The use of footwear, likely thongs (Australian term) or flip-flops (American term), is supported as a minimum. Such footwear needs to be well fitting, with the foot not projecting over the edge of the sole. It is useful for EPR, but will not protect when surface streamers are active, nor from a direct strike.

A combination of these strategies may offer inexpensive possibilities, which while not offering total protection, will offer partial improvement in protection.

VIII. ACKNOWLEDGEMENTS

The writer acknowledges helpful and challenging conversations with Professor Mary Ann Cooper, whose

endeavours in lightning protection in developing communities are substantial, with challenge to conventional paradigms of lightning science.

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