2014 23rd International Lightning Detection Conference
18 - 19 March • Tucson, Arizona, USA
5th International Lightning Meteorology Conference
20 - 21 March • Tucson, Arizona, USA

Backcountry Lightning Risk Reduction— Lightning Crouch Versus Standing With Feet Together

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***Abstract*—A model for evaluating backcountry risk reduction was previously developed. The backcountry lighting risk reduction model considers the relative frequency of the five mechanisms of lightning casualty and the risk reduction for each mechanism for any specified procedure. The five mechanisms of lightning casualties are: direst strike, contact voltage, side flash, step voltage/ground streamer, and upward leader.**

The backcountry lightning risk reduction model is now used to compare the risk reduction of using the lightning crouch versus standing with feet together. This is done for both a flat open field and a dense forest. While crouching reduces the risk from direct strikes, upward leaders, and in some cases side flash, details of the calculation previously suggested that most of the benefit comes from having your feet together rather than decreasing your height.

This new study formalizes the analysis and quantifies the difference. The results indicate that the lightning crouch reduces the risk of a lightning casualty by only a few percent and that the difference is not statistically significant, though likely physically real. However, a simpler guideline would be easier to do, remember, and more likely be done correctly. Therefore, modifying backcountry lightning risk reduction to replace the lightning crouch with standing with feet together should be considered.

It is prudent to emphasize that outdoor risk reduction should only be used as a desperate last resort—'<u>NO</u> Place Outside Is Safe When Thunderstorms Are In The Area!'

***Keywords*—lightning outdoor risk reduction; backcountry lightning; lightning crouch**

I. Introduction

The fundamental principle of lightning safety is '**<u>NO</u>** Place Outside Is Safe When Thunderstorms Are In The Area!' Lightning safety education should emphasize planning to avoid the threat and knowing when and where to go for safety. While the vast majority of lightning fatalities in the U.S. had safe locations nearby, there are some cases where safe locations were not quickly available, e.g. people in the backcountry. While no place outside is safe from lightning, the risk can be reduced.

Outdoor risk reduction guidelines have been developed for people without lightning safe locations nearby (Gookin, 2012; Gookin, 2010). A method to evaluate the effectiveness of those guidelines has been developed (Roeder, 2012; Roeder, 2009; Roeder, 2008a; Roeder, 2008b; Roeder, 2007). This paper applies that method to evaluate a variation of the outdoor lightning risk reduction guidelines. Specifically, the present guidelines using the lightning crouch as part of the process as compared to the variation substituting just standing with feet together. While the lightning crouch does provide some degree of additional safety, just standing with feet together is simpler, easier to remember and more likely to be done correctly, especially under the stress of avoiding lightning danger. So is the extra complexity of the lightning crouch worth the gain in risk reduction it provides? This paper evaluates the gain in risk reduction so that this question can be answered effectively.

It is prudent to emphasize that backcountry lightning risk reduction should only be used as a desperate last resort as the fourth of the five levels of lightning safety. The five levels of lightning safety are: 1) schedule outdoor events to avoid lightning, 2) know when and where to go for lightning safety, 3) reduce the risk if you must be outside with thunderstorms in the area, 4) outdoor risk reduction, and 5) first-aid.

II. Backcountry Lightning Risk Reduction

Two versions of backcountry lightning risk reduction will be evaluated: 1) the present guideline, and 2) the present guideline except that the lightning crouch is replaced with standing upright with feet together. The present guideline is summarized below.

No-notice personal backcountry lightning risk reduction is a multi-step process. It is meant to be used

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only as a desperate last resort. If you have made one or more bad decisions and find yourself outdoors, unprepared, far from a safe place when thunderstorms are threatening, you should proceed quickly to the safest place you can find. Places of greatest risk from lightning include elevated places, open areas, tall isolated objects, and large bodies of water. The safest places from lightning are a large fully enclosed building with wiring and plumbing, and a vehicle with solid metal roof and solid metal sides. While on the way to the safest place you can find, if in a group, spread out with about 6 m (20 ft) between people so that if lightning strikes, at most only one person will likely be hurt and the rest can apply first aid. But people should be close enough so they can communicate easily verbally. That way one person can shout a pre-agreed warning if the signs of imminent lightning are detected. While on the way to the safest place available, watch for the signs that lightning may be about to strike: hair standing up, light metal objects vibrating, or a crackling static-like sound from the air. If any of those signs are detected, shout the pre-agreed warning and everyone should immediately use the lightning crouch. The lightning crouch consists of putting your feet together, squatting, tucking your head, and covering your ears. After about 10 seconds, slowly stand while looking for the signs that lightning may still be about to strike. If you can stand up, continue on to the safest place available. The lightning crouch is also commonly known as the 'lightning squat', the 'lightning desperation position', and other names. Procedures for when you reach the safest place are under consideration, perhaps incorporating that part of the guidance from Gookin and Berc (2012) and Gookin (2010).

It should be reemphasized that this no-notice personal backcountry lightning risk reduction procedures should only be used as a desperate last resort. You are much safer to plan ahead and avoid such situations.

III. Evaluation Model

A simple model to evaluate the effectiveness of no-notice personal backcountry lightning risk reduction was developed previously (Roeder, 2012; Roeder, 2009; Roeder, 2008a; Roeder, 2008b; Roeder, 2007). One of these papers (Roeder, 2009) is reproduced in Appendix-1 to provide full details on the model and to allow this paper to focus on the pertinent changes for this new analysis.

The model to evaluate the effectiveness of backcountry lightning risk reduction focuses on the five mechanisms of lightning casualties. The five mechanisms and their percentage contribution to lightning fatalities are listed in Table-1. The differences between using the lightning crouch and standing with feet together in each of the five mechanisms are discussed below.

A) Direct Strike

A direct strike is a casualty caused by the lightning striking a person directly. Although this is usually the casualty mechanism most people envision, it is actually the cause of only about 4% of all lightning casualties, i.e. most of the other lightning casualty mechanisms are much more important that direct strike (Table-1).

In a wide flat field, the lightning crouch reduces the risk of a direct strike to 52.6% of taking no action, as calculated by a lightning protection model (Mata and Rokov, 2008) and as discussed in Appendix-1. However, this assumes the signs of an imminent lightning will be detected in every event and proper action taken in time. As discussed in Appendix-1, the most conservative assumption is that imminent lightning is detected by a person in 50% of the cases. Therefore, allowing for detection of imminent lightning decreases the risk reduction of the lightning crouch from a direct strike to 76.3% of taking no action. Standing with feet together has 100% of the risk of a direct strike compared to taking no action, i.e. no risk reduction, regardless if signs of imminent lightning are detected or not.

In a large dense forest, the chance of a direct strike is zero regardless if the lightning crouch is used or standing with feet together.

B*) Contact Voltage*

A contact voltage casualty is caused by a person being in direct contact with an object struck by lightning. Both versions of the backcountry lightning guidelines eliminate this risk. As a result, the risk of a contact voltage is 0% of taking no action for both versions of the guidelines and for both a wide flat field and a large dense forest. Since a person using the backcountry lightning risk reduction guidelines would already be away from tall objects when thunderstorms are in the area, a correction for detecting the signs of imminent lightning is not needed.

C) Side Flash

A side flash is caused by a person being close enough to an object struck by lightning so that some of the lightning arcs sideways to the person. About 31% of all lightning casualties are due to side flash.

The risk reduction procedure requires one to stay away from tall objects. As a result, the risk of side flash is 0% of taking no action in a wide flat field regardless if the lightning crouch or standing with feet together is used.

TABLE 1.
The lightning casualty mechanisms and the percentage of lightning casualties due to them.

Lightning Casualty Mechanism	Range of Percentage Of Casualties (%) (Cooper and Holle, 2010)	Mean Percentage of Casualties (%)	Scaled Mean (%) (scaled to sum to 100%)
Direct Strike	3-5%	4.0%	3.8%
Contact Voltage	3-5%	4.0%	3.8%
Side Flash	30-35%	32.5%	30.8%
Step Voltage/ Ground Streamer	50-55%	52.5%	49.8%
Upward Leader	10-15%	12.5%	11.8%

However, in a dense forest, it may not be possible to stay far enough away from the trees to avoid the risk of side flash, especially when rushing to the safest place available. In a large dense forest, the risk of side flash is different if using the lightning crouch or standing with feet together. The risk of side flash is assumed to be directly proportional to the amount of vertical exposure to the nearby tall object. The horizontal distance will be the same for the lightning crouch and standing with feet together and thus need not be taken into account. Another assumption is that the risk of side flash is zero for a flat object on the ground. The lightning crouch reduces a person's height to 44.4% of standing upright and so reduces the risk of side flash in a large dense forest to 44.4% of taking no action. This number is different than for a direct strike since the effect of 'looking distance' is not a factor for side flash. Allowing for when imminent lightning is not detected, the lightning crouch reduces the risk of side flash in a large dense forest to 72.2% of taking no action.

D) Step Voltage/Ground Streamer

The return stroke in cloud-to-ground lightning can cause casualties through a step voltage or ground streamer. The step voltage and ground streamers can cause casualties up to a few tens of meters from the return stroke. Step voltage and ground streamer account for about 50% of lighting casualties.

The lightning crouch does not reduce the chance of a casualty from step voltages since most people do not put their feet together while crouching since it is difficult to keep your balance. So it is assumed that people crouching will have their feet the same distance apart as in standing and so there is no risk reduction from step voltages. However, the lightning crouch also reduces the chance of a casualty from ground streamers by reducing the area touching the ground since most people will balance on the balls of their feet. As calculated in Atch-1, the risk reduction is 66%. As before, not detecting imminent lightning must be accounted for, reducing the benefit to 83%.

Standing with your feet together is much easier than crouching with your feet together, It is assumed the typical distance between the outer edges of the feet for normal standing is 0.533 m (21 inches) and 0.203 m (8 inches) while standing with feet together. The ratio of these lengths and thus the relative risk from step voltages is 38.1% Allowing for imminent lightning being detected only half the time, the effective relative risk becomes 69.1% Assuming people will stand flat footed and there is no decrease in area touching the ground and no risk reduction from ground streamers.

The risk reduction from step voltage and ground streamer is the same for a forest and a flat open field. The risk reduction is also the same both versions of the backcountry guidelines since both the lightning crouch and standing with your feet together reduce the risk of step voltage and ground streamer by the same amount.

E) Upward Leader

The fifth and final source of lightning casualty is upward streamer. Upward leaders account for about 12% of lightning casualties. The calculations of risk reduction in a wide flat field and forest and for using the lightning crouch or standing with feet together are the same as for direct strike.

F) Error Estimate

The error bars due to the uncertainty in people perceiving the precursors of imminent lightning were calculated for a wide flat field and a large dense forest. A second source of error is the relative frequency of lightning casualties resulting from the lightning mechanisms. An inter-quartile variation is calculated for both sources of error. Since the two sources of error are independent, the total inter-quartile error is calculated by the root sum of the squares of the two errors. These results are summarized in Table-6.

TABLE 2.

Estimated risk of lightning casualty in a **wide flat field** using the present backcountry lightning risk reduction guideline, i.e. **using the lightning crouch**. The total risk is ≅ 53% of taking no action, i.e. a 47% reduction of risk.

Lightning Casualty Mechanism	**Percent of Lightning Casualties**	**Estimated Relative Risk If Using Backcountry Lightning Risk Reduction** (lower = less risk)	**Estimated Casualty Rate Vs. Taking No Action** (%-casualties x relative risk)
Direct Strike	3.8%	76% (87.9% to 64.2%)*	2.9% (3.3% to 2.4%)*
Contact Voltage	3.8%	0% (0% to 0%)*	0% (0% to 0%)*
Side Flash	30.8%	0% (0% to 0%)*	0% (0% to 0%)*
Step Voltage/ Ground Streamer	49.8%	83% (91.3% to 74.7%)*	41.3% (45.5% to 37.2%)*
Upward Leader	11.8%	76% (87.9% to 64.1)*	9.0% (10.4% to 7.6%)*
			SUM = 53.2% (59.2% to 47.2%)* ≅ 53% ± 6%

* The risk depends on how frequently the signs that imminent lighting are perceived with sufficient lead-time to take action. The number before the parentheses is the best estimate, assuming that half of the events will have adequate lightning precursors. The numbers in the parentheses are a 50% confidence interval assuming that lightning precursors are detected in 25% of the vents and 75% of the events. The sum of errors is assumed to add linearly, rather than the more likely RMS addition, to provide a conservative estimate of the total error and to help allow for other sources of error not accounted for here.

TABLE 3.

Estimated risk of lightning casualty in a **large dense forest** using the present backcountry lightning risk reduction guideline, i.e. **using the lightning crouch**. The total risk is ≅ 65% of taking no action, i.e. a 35% reduction of risk.

Lightning Casualty Mechanism	**Percent Of Lightning Casualties Of Average Behavior** (Cooper and Holle, 2010)	**Estimated Relative Risk If Using Backcountry Lightning Risk Reduction** (lower = less risk)	**Estimated Casualty Rate Vs. Taking No Action** (%-casualties x relative risk)
Direct Strike	3.8%	0% (0% to 0%)*	0% (0% to 0%)*
Contact Voltage	3.8%	0% (0% to 0%)*	0% (0% to 0%)*
Side Flash	30.8%	72% (86.1% to 58.3%)*	22.2% (26.5% to 18.0%)*
Step Voltage/ Ground Streamer	49.8%	83% (91.3% to 74.7%)*	41.3% (45.5% to 37.2%)*
Upward Leader	11.8%	0% (0% to 0%)*	0% (0% to 0%)*
			SUM = 63.5% (72.0% to 55.2%)* ≅ 64% ± 8%

* The risk depends on how frequently the signs that imminent lighting are perceived with sufficient lead-time to take action. The number before the parentheses is the best estimate, assuming that half of the events will have adequate lightning precursors. The numbers in the parentheses are a 50% confidence interval assuming that lightning precursors are detected in 25% of the vents and 75% of the events. The sum of errors is assumed to add linearly, rather than the more likely RMS addition, to provide a conservative estimate of the total error and to help allow for other sources of error not accounted for here.

TABLE 4.

Estimated risk of lightning casualty in a **wide flat field** using the variation of the backcountry lightning risk reduction guideline using **standing with feet together** instead of the lightning crouch. The total risk is ≅ 57% of taking no action, i.e. a 43% reduction of risk.

Lightning Casualty Mechanism	**Percent of Lightning Casualties**	**Estimated Relative Risk If Using Backcountry Lightning Risk Reduction** (lower = less risk)	**Estimated Casualty Rate Vs. Taking No Action** (%-casualties x relative risk)
Direct Strike	3.8%	100% (100% to 100%)*	3.8% (3.8% to 3.8%)*
Contact Voltage	3.8%	0% (0% to 0%)*	0% (0% to 0%)*
Side Flash	30.8%	0% (0% to 0%)*	0% (0% to 0%)*
Step Voltage/ Ground Streamer	49.8%	69.1% (84.5% to 53.6%)*	34.4% (42.1% to 26.7%)*
Upward Leader	11.8%	100% (100% to 100%)*	11.8% (11.8% to 11.8)*
			SUM = 50.0% (57.7% to 42.3%)* ≅ 50% ± 8%

* The risk depends on how frequently the signs that imminent lighting are perceived with sufficient lead-time to take action. The number before the parentheses is the best estimate, assuming that half of the events will have adequate lightning precursors. The numbers in the parentheses are a 50% confidence interval assuming that lightning precursors are detected in 25% of the vents and 75% of the events. The sum of errors is assumed to add linearly, rather than the more likely RMS addition, to provide a conservative estimate of the total error and to help allow for other sources of error not accounted for here.

TABLE 5.

Estimated risk of lightning casualty in a **large dense forest** using the variation of the backcountry lightning risk reduction guideline using **standing with feet together** instead of the lightning crouch. The total risk is ≅ 72% of taking no action, i.e. a 28% reduction of risk.

Lightning Casualty Mechanism	**Percent Of Lightning Casualties Of Average Behavior** (Cooper and Holle, 2010)	**Estimated Relative Risk If Using Backcountry Lightning Risk Reduction** (lower = less risk)	**Estimated Casualty Rate Vs. Taking No Action** (%-casualties x relative risk)
Direct Strike	3.8%	0% (0% to 0%)*	0% (0% to 0%)*
Contact Voltage	3.8%	0% (0% to 0%)*	0% (0.0% to 0%)*
Side Flash	30.8%	100% (100% to 100%)*	30.8% (30.8% to 30.8%)*
Step Voltage/ Ground Streamer	49.8%	69.1% (84.5% to 53.6%)*	34.4% (42.1% to 26.7%)*
Upward Leader	11.8%	0% (0% to 0%)*	0% (0% to 0%)*
			SUM = 65.2% (72.9% to 57.5%)* ≅ 65% ± 8%

* The risk depends on how frequently the signs that imminent lighting are perceived with sufficient lead-time to take action. The number before the parentheses is the best estimate, assuming that half of the events will have adequate lightning precursors. The numbers in the parentheses are a 50% confidence interval assuming that lightning precursors are detected in 25% of the vents and 75% of the events. The sum of errors is assumed to add linearly, rather than the more likely RMS addition, to provide a conservative estimate of the total error and to help allow for other sources of error not accounted for here.

TABLE 6.

Error estimates of no-notice personal backcountry lightning risk reduction for a flat open field and a large dense forest. All the error estimates are inter-quartile ranges.

Source Of Error	Flat Open Field		Large Dense Forest	
	Lightning Crouch	Standing With Feet Together	Lightning Crouch	Standing With Feet Together
Frequency that signs of imminent lightning detected with enough lead-time to react	± 6.0%	± 4.2%	± 7.7%	± 7.7%
Uncertainty in the relative frequency of lightning casualties from each lightning casualty mechanism	± 3%			
Total Error (RMSE of above errors)	**± 6.7%**	**± 5.2%**	**± 8.3%**	**± 8.3%**

TABLE-7

Estimated casualty rate vs. taking no action for various scenarios. Parentheses are 50% confidence intervals that include both sources of uncertainty: detecting signs of imminent lightning with enough lead-time to react, and relative frequency of the lightning casualty mechanisms.

Backcountry Guideline	**Wide Flat Field**	**Large Dense Forest**
Using lightning crouch	53.2% (59.9% to 46.5%)	63.5% (71.8% to 55.2%)
Using standing with feet together instead of lightning crouch	50.0% (55.2% to 44.8%)	65.2% (73.5% to 56.9%)
Difference between using lightning crouch and standing with feet together	+3.2% (lightning crouch risker)	-1.7% (lightning crouch less risky)

G) Model Results

The calculations of the backcountry lightning risk reduction model for a flat wide field and large dense forest using the lightning crouch and just standing with feet together are shown in Table-2, Table-3, Table-4, and Table-5, respectively. The details of the calculation process are in Appendix-1. The final results are summarized in Table-7.

The lightning crouch had -1.7% of the risk as compared to standing with feet together in a large dense forest, i.e. the lightning crouch is less risky in that scenario. However, the lightning crouch had +3.2% of the risk of standing with feet together, i.e. the lightning crouch had more risk in that scenario. These differences are smaller than the error estimates and so are not statistically significant, although likely physically real.

If one considers a wide flat field and large dense forest as two extremes of outdoor lightning risk reduction scenarios, then an overall comparison of the lightning crouch as compared to standing with feet together could be the average of the two risk comparisons. This average is +0.75%, i.e. in general the lightning crouch has more risk than standing with feet together. The difference is not statistically significant, although is likely physically real.

H) Recommendation

It is recommended to modify backcountry lightning risk reduction procedures to replace the lightning crouch with standing with feet together for two main reasons:

- Reason-1: The lightning crouch is more difficult to perform than standing with feet together. It is also more complex and thus more likely to be remembered and applied incorrectly.
- Reason-2: The lightning crouch offers insignificant benefit to insignificant detriment depending on the scenario as compared to standing with feet together. It provides an overall insignificant detriment.

IV. Future Work

There is considerable uncertainty in the analysis of the effectiveness of last minute outdoor lightning risk reduction. The estimate of how frequently the precursors to a lightning strike occur in the few seconds before the strike and are observed by people in time to take action is especially uncertain. The relative contribution of the five lightning casualty mechanisms to the total casualty rate is also not well known. Therefore, the estimate of the risk reduction from the last minute personal backcountry lightning risk reduction is only a rough approximation. All these estimates need to be refined.

Another possible way to improve the guidelines is to add recommendations on what to do once you reach the safest location available, perhaps based on Gookin (2012; 2010). In particular, the benefit of being on an electric insulator should be analyzed for possible inclusion in the guidelines, e.g. sitting or standing on a sleeping pad or backpack useful. For example, the insulator may only be effective near the edge of the range over which step currents and ground streamers are dangerous. If that is the case, the insulators would not provide much protection under most conditions. If so, adding this guidance may overly complicate the guidelines, give a false sense of security, and perhaps lead to poor decisions, e.g. people staying in a risky location during a thunderstorm thinking the insulator offers good protection.

Other possibilities include an estimate of the risk reduction for different no-notice personal backcountry risk reduction procedures. The risk reduction estimates should also be performed for other locations than a flat open field and a large dense forest, e.g. mountains above and below the tree line, small stand of trees, uneven terrain, small groups of people versus just individuals, etc.

The estimate of frequency of lightning casualties that were near a safe location should be refined since that is one of the key arguments in recommending last minute outdoor lightning risk reduction not be taught to the general public.

Finally, the physiological assumptions made in the analysis of backcountry risk reduction should be verified and the calculations adjusted as needed. These assumptions include: average height while standing and crouching, change in distance between feet while standing and crouching, average span of feet while standing with feet together, etc.

These topics and other research required to improve lightning safety are listed at Roeder (2009a, 2009b). This list has been significantly updated since those publications and is available from the author (william.roeder@patrick.af.mil).

V. Summary

The model to evaluate the effectiveness of no-notice personal backcountry lightning risk reduction has been applied to two versions of backcountry lightning risk reduction procedure: 1) the present version that uses the lightning crouch as part of the procedure, and 2) standing with feet together replacing the lighting crouch. The results are summarized in Table-7. Using the lightning crouch reduces risk by only 1.7% in a large dense forest as compared to standing with feet together and actually increases the risk by 3.2% in a wide flat field. This suggests the overall result is a detriment of 0.75% for the lightning crouch as compared to standing with feet together. While these differences are not statistically significant, they are likely physically real. This suggests that the guideline for backcountry lightning risk reduction should be modified to replace the lightning crouch with standing with feet together. The simpler guideline would be easier to use, especially for extended periods. The new guideline would also be easier to remember and use correctly.

VI. Acknowledgements

The risk reduction from a direct lightning strike from using the lightning crouch versus standing upright in a wide flat field was provided by Dr. Mata of ASRC Aerospace, Inc. at NASA Kennedy Space Center. He used a Monte Carlo model that simulates 1,000 years of lightning strikes, varying the lightning "looking distances" based on the climatological distribution of negative polarity cloud-to-ground lightning and their distribution of peak currents (Mata and Rokov, 2008).

VII. Disclaimer

This paper is presented for informational purposes only and no guarantee of lightning safety is stated or implied by the procedures.

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APPENDIX-1

(Roeder, 2009)

JP1.2 LAST MINUTE OUTDOOR LIGHTNING RISK REDUCTION— A METHOD TO ESTIMATE ITS EFFECTIVENESS AND COMMENTS ON ITS UTILITY IN PUBLIC EDUCATION

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1. INTRODUCTION

This paper presents updates to previously published analysis of last minute outdoor lightning risk reduction (Roeder, 2008a, 2007a). In particular, the error estimates and opportunities for future research have been improved.

Lightning is the second leading cause of storm deaths in the United States, killing more people on average each year than tornadoes or hurricanes (NOAA, 2006). Lightning also causes life-long debilitating injuries on many more than it kills (Cooper, 1995). Lightning is also a significant weather hazard outside of the U.S. (Holle and Lopez, 2003). Fortunately, public education is a cost effective solution to much of the problem and there is strong consensus on lightning safety recommendations.

However, last minute outdoor lightning risk reduction was discussed extensively in the lightning safety community during 2006, especially within the working group for the U.S. National Weather Service annual lightning safety awareness week and among the board of directors of StruckByLightning.Org, a non-profit lightning safety education organization. The debate focused on what constitutes good last minute outdoor lightning risk reduction, its effectiveness, and whether it should be taught. The 'last minute' part refers to what individuals can do to protect themselves when outside, away from a safe place, and thunderstorms threaten with little lead-time. This is as opposed to when thunderstorms are in the area, but not immediately threatening, and people can not go to a safe place. In that case, people can reduce their risk by avoiding risky locations and activities. This is also as opposed to institutional outdoor lightning risk reduction, e.g. adding lightning protection to frequently-used at-risk areas, lightning detection/notification systems, etc. The longer range individual actions and the institutional aspects will not be discussed.

Last minute outdoor procedures reduce the risk of lightning casualty to 47% ± 7% of that of standing and taking no protective action. While many of assumptions in this estimate are uncertain, the overall result is fairly insensitive to them, since the error bars on the estimate are only ± 7% for an inter-quartile range.

It is important to note the use of the term 'risk reduction' when discussing last minute outdoor lightning risk reduction. The fundamental principle of lightning safety is 'no place outside is safe when thunderstorms are in the area' (Roeder et al., 2001). This is not mere legalistic word selection, but promotes a proper attitude towards lightning safety and reduces improper outdoor applications.

Meteorologists, especially broadcast meteorologists, or anyone else involved with lightning, are encouraged to proactively teach lightning safety to the public. Those interested in teaching lightning safety will find a recommended approach at Roeder (2008b, 2007b) and useful resources at the National Weather Service website on this topic (www.lightningsafety.noaa.gov). They may also contact the author for assistance (wroeder@cfl.rr.com).

2. Last Minute Outdoor Lightning Risk Reduction

Last minute outdoor lightning risk reduction is a multi-step process. It is meant to be used only as a desperate last resort. If you have made one or more bad decisions and find yourself outdoors, far from a safe place when thunderstorms are threatening, you should proceed quickly away from risky locations to the safest place you can find. Places of greatest risk from lightning include elevated places, open areas, tall isolated objects, and large bodies of water. The safest places from lightning are a large fully enclosed building with wiring and plumbing, and a vehicle with solid metal roof and solid metal sides. While on the way to the safest place you can find, if in a group, spread out with about 5 m between people so that if lightning strikes, at most only one person will likely be hurt and the rest can apply first aid. While on the way to the safest place available, watch for the signs that lightning may be about to strike: hair standing up, light metal objects vibrating, or a crackling static-like sound from the air. If any of those signs are detected, everyone should immediately use the lightning crouch. The lightning crouch consists of putting your feet together, squatting, tucking your head, and covering your ears. After about 10 seconds, slowly stand while looking for the signs that lightning may still be about to strike. If you can stand up, continue on to the safest place available. The lightning crouch is also commonly known as the 'lightning squat', the 'lightning desperation position', and other names. It should be emphasized again that these outdoor lightning risk reduction procedures should only be used as a desperate last resort. You are much safer to plan ahead and not get into such situations.

3. Effectiveness Of Last Minute Outdoor Lightning Risk Reduction

Lightning causes casualties through five main mechanisms: 1) direct strike, 2) contact voltage, 3) side flash, 4) step voltage or ground streamers, and 5) upward leader. The relative frequency of lightning casualties from each mechanism has been estimated over a wide range of values (Cooper et al., 2006a, 2006b) (Roeder, 2008a). The most recent and best estimates are presented at this conference (Cooper et al., 2008) and are adapted for use in this paper. Due to the uncertainties in the estimates, Cooper at al. (2008) provided a range of values for each casualty mechanism. In lieu of any evidence for a preferred value, the author used the mean of each range to minimize the expected error. The means were then scaled so they would sum to 100%, to assure internal consistency (Table 1).

The next step was to estimate the relative risk reduction of the last minute outdoor procedures for each mechanism. The total risk reduction was then calculated by multiplying the risk reduction for each mechanism by the relative frequency of that mechanism in causing lightning casualties. Summing across these multiplicative products then gives an estimate of the total risk reduction of the proscribed last minute outdoor lightning risk reduction procedure. This process is discussed in more detail in the following sections.

The total risk of last minute outdoor lightning risk reduction is $47\% \pm 7\%$ for an inter-quartile range estimate for the error bars. While this reduction may sound significant, it is still too risky, given the devastating impacts lightning. The relative risk for each lightning casualty mechanism is calculated below.

TABLE 1. Relative frequency of lightning casualty mechanisms.

Mechanism	Range (%) (Cooper et al., 2008)	Mean (%)	Scaled Mean (%) (scaled to sum to 100%)
Direct Strike	3-5	4.0	4
Contact Voltage	15-25	20.0	19
Side Flash	20-30	25.0	23
Step Voltage/ Ground Streamer	40-50	45.0	42
Upward Leader	10-15	12.5	12

3.1. Direct Strike

Consider the idealized case of a single person in a flat infinite area with no vertical obstructions. The person is an average height of 1.8 m and is 0.8 m tall in the lightning crouch. Using the standard 'rolling sphere method' with a 50 m radius used in many lightning protection standards (NFPA, 2004), the relative threat of a direct strike is proportional to the area over which the step leader connects to the person. Under these conditions, the lightning crouch reduces a chance of a direct lightning strike to 45% of that of standing. Table 3 summarizes the calculations with the model shown graphically in Figure 1. This flat open field model provides an upper limit to the risk reduction provided by the lightning crouch in the real world.

A more refined approach is provided by the proprietary lightning protection software used by ASRC Aerospace, Inc. at NASA Kennedy Space Center to help design lightning protection systems for facilities with complex structures (Mata and Rakov, 2008). This software uses a Monte Carlo simulation of lightning strikes randomly distributed horizontally with the local flash density. It uses the rolling sphere method but varies the strike distances depending on the intensity of each simulated lightning flash, rather than a constant median strike distance of 50 m. The intensity of each flash is varied randomly according to U.S.-wide climatological frequency of occurrence of negative and positive polarity flashes and the U.S.-wide climatological frequency distribution of lightning peak currents for each polarity. With a local cloud-to-ground flash density of 17 Flashes/Km^{2}Yr, a 1.8 m standing person was struck by 1.9% of the flashes over a simulated 1,000-year period. A crouching person at 0.8 m was struck by only 1.0% of the flashes during the same simulation.

TABLE 2. Estimated Risk of lightning casualty using last minute outdoor lightning risk reduction procedures. The total risk is 47%.

Lightning Casualty Mechanism	**Percent Of Lightning Casualties Of Average Behavior** (Cooper at al., 2008)	**Estimated Relative Risk If Using Last Minute Outdoor Lightning Risk Reduction** (lower = less risk)	**Estimated Casualty Rate Vs. Average Behavior** (%-casualties x relative risk)
Direct Strike	4%	76% (88.0% to 64.3%)*	3% (3.5% to 2.6%)*
Contact Voltage	19%	0%	0%
Side Flash	23%	0%	0%
Step Voltage/ Ground Streamer	42%	83% (91.5% to 74.85%)*	35% (38.4% to 31.4%)*
Upward Leader	12%	76% (88.0% to 64.3)*	9% (10.5% to 7.7%)*
			SUM = 47% (52.5% to 41.7%)* ≅ 47% ± 6%

* The risk depends on how frequently the signs that imminent lighting are perceived with sufficient lead-time. The number before the parentheses is the best estimate, assuming that half of the events will have adequate lightning precursors. The first number in the parenthesis is a first quartile estimate that assumes lightning precursors are perceived only 25% of the time, halfway from the best estimate to the extreme case that lightning precursors are never perceived. The second number in the parenthesis is a third quartile estimate that assumes lightning precursors are perceived 75% of the time, halfway from the best estimate to the extreme that lightning precursors are always perceived.

TABLE 3. Strike area for a standing person versus a crouching person using a 50 m 'rolling sphere' in a flat infinite area with no vertical obstructions. In this model, crouching reduces the chance of a direct lightning strike to 45% of standing. A more sophisticated model, discussed in the text, shows the lightning crouch has 52.6% chance of a direct strike compared to standing, and is the preferred estimate.

Attachment Point	**Step Leader Horizontal Distance From Person (m)**	**Area Of Strike Distance (m^2)**	**Ratio Of Crouching To Standing Strike Area**
Standing Person (1.8 m)	0.0 to 13.3	555.7	0.448
Crouching Person (0.8 m)	0.0 to 8.9	248.8	
Ground	> 13.3 m	N/A	

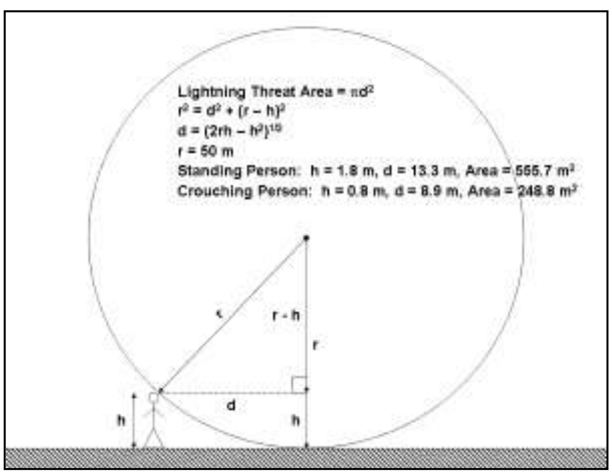

Figure 1. Model used to check the order of magnitude of the Monte Carlo simulation of the risk reduction of the lightning crouch for a direct lightning strike—50 m rolling sphere in an infinite flat area with no obstructions.

This implies the lightning crouch gives a risk reduction of a direct strike to 52.6% chance of that of a standing person. The 45% from the simplified lightning crouch model above is within the error bars of the Monte Carlo simulation by Mata and Rakov (2008). The risk reduction from the simplified model was calculated as a consistency check on the Monte Carlo model. Since this Monte Carlo model considers the distribution of lightning strike distances for both positive and negative polarity lightning, its solution of crouching providing 52.6% the risk of standing is the preferred solution.

However, the above analysis implicitly assumes that the signs of imminent lightning will always be perceived with enough lead-time to take full action. This is unlikely to be the case. The frequency of adequate signs of imminent lightning is not known. However, the author's limited experience with nearby lightning is that rising hair and vibrating metal are not often observed. While

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the static-like sound is often noted, it provides only 1-2 seconds of lead-time. If adequate lightning precursors are never perceived, then the lightning crouch is completely ineffective since it won't be used and provides 100% of the risk of standing. In lieu of good information, assume that 50% of the time there will be a sign of imminent lightning with enough lead-time to use the lightning crouch. This assumption minimizes the error that would result from choosing one of the extremes of always having notice and never having notice and is common practice in risk management. In the assumed 50% of the time that sufficient notice is perceived, the risk drops to 52.6% of standing. The other 50% of the time there will not be an adequate sign of imminent lightning and the risk will be 100% of standing (no action can be taken). The frequency weighted average of these two risks gives an overall risk of 76.3% of a direct strike as compared to standing. Therefore, the effectiveness of the lightning crouch ranges from 52.6% to 100% of the risk of standing, depending if lightning precursors are always or never perceived, respectively, with a best estimate of 76.3% of standing.

3.2 Contact Voltage

Lightning can inflict casualties through contact voltage. If a person is standing on the ground and touching an object that receives a direct lighting strike, there will be a voltage change across their body that will cause an electric current to flow through them. Since people are mostly salt water and are an adequate electrical conductor, they are usually the path of less resistance (technically impedance) than a tree, and a majority of the lightning current will be diverted through them to the ground. Last minute outdoor lightning risk reduction starts with rushing away from risky locations and to the safest spot available, which includes not touching objects likely to be struck directly by lightning, such as tall isolated objects like trees. Therefore, last minute outdoor lightning risk reduction virtually eliminates the risk of contact voltage, if followed properly.

3.3 Side Flash

A side flash occurs when a path of less resistance (technically impedance) to electrical ground exists close enough to an object that has been struck directly by lightning. The lightning arcs across the air gap to the lower resistance/impedance object. For a tree and a person, the distance a lightning side flash can travel is limited to about 3 m. Last minute outdoor lightning risk reduction starts with rushing away from risky locations and to the safest spot available, which includes keeping away from as tall isolated objects that are likely to be struck but lightning. Therefore, last minute outdoor lightning risk reduction virtually eliminates the risk of side flash, if followed properly.

3.4 Step Voltage/Ground Streamer

As lightning reaches the ground, it can still cause casualties as it dissipates by step voltage or ground streamer. The step voltage is a roughly radial voltage gradient along the surface of the ground. If a person is standing with their feet apart with the proper orientation, then a strong voltage change occurs across the person inducing a potentially deadly current. A ground streamer is a large spark along the ground arcing between the grains of soil. If one of these ground streamers coincidentally touches a person's foot, the current will race through the person since they are a path of less resistance (technically impedance) as compared to the soil. The lightning crouch is meant to reduce the risk of step voltage by placing the feet together—the less the distance between your feet, the less the voltage drop across the body. However, when squatting with feet together, it is difficult to keep your balance. When squatting, many people place their feet apart with about the same distance when standing. There is also the risk that they will forget this detail under the stress of a lightning threat. Thus, the lightning crouch provides essentially no risk reduction against step voltage in the real world. However, the lightning crouch may provide some risk reduction against ground streamers since most people balance on the balls of their feet. This reduces the area touching the ground to about 1/3 if standing normally. Thus the lightning crouch reduces the risk from ground streamers to about 1/3 that of standing. The relative frequency of step voltage and ground streamer in lightning casualties is not well known. In lieu of any good information, assume that they cause lightning casualties with equal frequency. Thus the total risk reduction is the weighted average of 100% (no risk reduction) for step voltages and 33.3% for ground streamers, or a combined overall 66.7% of the risk of standing.

As for 'direct strikes', we need to allow for signs of imminent lightning not always being perceived with enough lead-time to take full action. As in paragraph 2.a., assume that 50% of the time there will be a sign of imminent lightning with enough lead-time to use the lightning crouch and the risk drops to 67% of standing. Then rest of the time there will not be an adequate sign of imminent lightning and the risk will be 100% of standing. The frequency weighted average of these two risks gives an overall risk of 83% that of standing. Therefore, the effectiveness of the lightning crouch ranges from 67% to 100% of the risk of standing, depending if lightning precursors are always or never perceived, respectively, with a best estimate of 83% of standing.

3.5 Upward Leader

Upward leaders are sparks a few tens of meters that reach out of the ground from tall thin objects a split second before the lightning stroke. When an upward leader contacts a step leader, the return stroke initiates. The return stroke super heats the step leader path causing the flash of light and thunder, which is commonly referred to as the lightning stroke. The lightning crouch reduces the chance of a direct strike by reducing the chance of an upward leader forming. Thus, the lightning crouch reduces the chance of an upward leader by the same amount that it reduces the chance of a direct strike. A person has about a 53% chance of experiencing an upward leader in the lightning crouch as compared to standing. However, we must again allow for the signs of imminent lightning only being perceived with enough lead-time half the time. This produces a best estimate of risk of 76% compared to standing upright, with a range of 53% to 100% depending if lightning precursors are always or never perceived, respectively.

3.6 Error Estimate

The error bars for this estimate were calculated by redoing the calculations in Table 1 and allowing for two major sources of error. The total inter-quartile error is ± 7%.

The first major source of error is the frequency that lightning precursors are observed with enough lead-time for people to take the last minute outdoor lightning risk reduction actions. The second major source of error is the relative frequency of lightning casualties results from the lightning mechanisms. An inter-quartile variation is calculated for both sources of error. Since the two sources of error are independent, the total inter-quartile error is calculated by root sum of the squares of the two errors.

We have already seen that the last minute outdoor lightning risk reduction risk reduction procedure outlined previously is fairly insensitive to how often the precursors to an imminent lightning strike are perceived with sufficient lead-time and reacted to appropriately. As shown in Table 2, this gives error bars of only ± 6% around the nominal risk of 47%. The other assumptions are now examined to provide an extremely optimistic and an extremely pessimistic estimate.

In the upper quartile estimate, we assume that the lightning precursors are perceived and reacted to appropriately in 75% of the return strokes that threaten people. We also assume that people can do the lightning crouch with their feet together, so that the outside edges of their feet are 0.2 m apart, as opposed to 0.6 m when standing normally. This reduces their risk from step voltage to about 0.33 (0.2/0.6), assuming the voltage gradient along the ground from a nearby return strike does not change significantly over the 0.6 m distance at the typical distances of people from the return stroke. Redoing the total risk as in Table 2, but under these extremely optimistic assumptions, gives a total risk of 36% as compared to standing in the open area and taking no protective action.

In the lower quartile estimate, we assume that the lightning precursors are perceived in 0% of the return strokes and so people can of course not react to them appropriately. This renders moot any other pessimistic assumptions such as standing with feet a normal distance apart. This also means there will be no risk reduction from direct strike, ground streamer and step voltage, and upward leader. The only risk reduction will be from avoiding tall isolated objects and the risk reduction from no contact voltages or side flashes. This yields a risk of 58% of taking no actions. These results are summarized in Table 4.

Interestingly, this suggest that the majority of lightning risk reduction outdoors comes from avoiding tall isolated objects, such as not going under trees to keep dry. This has been part of lightning safety recommendations for decades. Adding looking for lightning precursors and using the lightning crouch provides only an additional 6% risk reduction, which is just within the error bars. This suggests that while the lightning crouch can be useful in reducing lightning casualties, in the real world it provides an insignificant, to at best small gain in risk reduction.

The second major source of error is the variation in relative contribution from the lightning casualty mechanisms. The inter-quartile error estimate for this source of error was calculated from the risk reductions from all combinations of the lower quartiles, upper quartiles, and nominal values for the five lightning casualties in Table 1. The values are rescaled to sum to 100% for each combination for internal consistency. Finally, the inter-quartile range of the risk reduction for all the combinations was calculated. The inter quartile range allowing for the uncertainties in the relative contributions of the lightning mechanisms is ± 3%.

The two major sources of error are independent of each other and so can be combined via root sum of squares to get a total error. The root sum of squares for the error from the uncertainty in observing lightning precursors (± 6%) and the uncertainty in the relative contribution of lightning mechanisms (± 3%) becomes the total inter-quartile error of ± 7%.

TABLE 4. Last minute outdoor lightning risk reduction under extremely optimistic, nominal, and extremely pessimistic assumptions.

ASSUMPTION	RISK RELATIVE TO TAKING NO ACTIONS
Upper Quartile Estimate (lightning precursors perceived and reacted to 75% of the time; lightning crouch done with feet together)	42%
Nominal (as discussed in Section 3 & summarized in Table 2)	47%
Lower Quartile Estimate (lightning precursors perceived and reacted to 25% of the time; lightning crouch done with feet together)	53%

4. Improvements In Future Work

There is considerable uncertainty in the analysis of the effectiveness of last minute outdoor lightning risk reduction. The estimate of how frequently the last second precursors to a lightning strike occur and are observed by people in time to take action is especially uncertain. The relative contribution of the five lightning casualty mechanisms to the total casualty rate is also not well known. Therefore, the relative improvement of the last minute outdoor lightning risk reduction over doing nothing is only roughly approximated. All these estimates need to be refined. In addition, the risk reduction analysis should be done for locations other than a large flat unobstructed area, e.g. forests, mountains above and below the tree line, etc. Finally, the estimate of frequency of lightning casualties that were near a safe location should be refined since that is one of the key arguments in recommending last minute outdoor lightning risk reduction not be taught to the general public. These topics and other research required to improve lightning safety are at Roeder (2009).

5. Comments On The Utility Of Last Minute Outdoor Lightning Risk Reduction In Public Education

5.1 Reasons Not To Teach This To The Public

Even though the last minute outdoor lightning risk reduction is effective, it should not be taught because of the devastating consequences of being struck by lightning and several education/communication difficulties. The reasons for not teaching last minute outdoor lightning risk reduction are discussed below and summarized in Table 5. However, teaching last minute outdoor lightning risk reduction may be appropriate for sophisticated users that spend large amounts of time far away from safe places from lightning.

This recommendation applies only to the 'last minute' part of last minute outdoor lightning risk reduction, when threatened by thunderstorms outdoors with no safe place available with little or no lead-time. Other parts of outdoor lightning risk reduction should still be taught, e.g. scheduling outdoor activities to avoid lightning and risky places to avoid if you must be outside when thunderstorms are in the area.

One of the main reasons not to teach last minute outdoor lightning safety is the devastating impacts of a lightning strike. Lightning can cause death or life-long debilitating injuries (Cooper, 1995). Even if the chances of a casualty are reduced by about half, the consequences are not worth even the reduced risk.

Lightning safety trainers have enough trouble getting people to curtail outdoor activities when lightning threatens. Since people tend to overly focus on the lighting crouch, this could decrease proper safety action in the misguided belief that the lightning crouch is a good idea. One of the reasons that people may have overly focused on the lightning crouch is it was the only picture of people taking action in many NOAA brochures. NOAA plans to reprint those brochures, when supplies are exhausted, with a picture of a person running to safety instead of the lightning crouch.

This focus on the lightning crouch can also lead to overconfidence in the effectiveness of the lightning crouch and other last minute outdoor lightning risk reduction. It is important to avoid this overconfidence since it may detract from the more important aspects of lightning safety, such as scheduling outdoor activities to avoid lightning, and avoiding risky locations when you must be outdoors when thunderstorms are in the area.

Teaching the lightning crouch can also give the appearance of contradicting the fundamental principle of lightning safety -- ‘no place outside is safe when thunderstorms are in the area’ (Roeder et al., 2001). This can undermine the credibility of lightning safety education, since most people will not catch the subtle but important distinction between safety and risk reduction.

The complexity of outdoor lightning risk reduction also causes people to misremember and misapply the lightning crouch frequently, especially under a high stress situation like an imminent lightning strike. A truism in training is that complex procedures can have problems under stressful situations. One of the common misapplications of the lightning crouch is that you should spend the whole storm in that position. This leads people to waste time that would be better spent seeking the safest place possible. The author has even seen a weather broadcaster advising children to use the lighting crouch in a playground rather then running into the school building only tens of meters away. The lightning safety community has seen other examples of people misremembering recommendations. The old ‘Flash To Bang’ method required people to estimate the time between lightning and its thunder, divide the number of seconds by 5 seconds per mile, and take action when lightning was within six miles. However, people frequently misremembered the conversion factor as 1 second per mile. This was one of the factors that led to the ’30-30 Rule’ (Holle et al., 1999); the conversion factor and distance are subsumed into the first ‘30’ (30 seconds corresponds to 6 miles). The other second ‘30’ in the ’30-30 Rule’ was the need to stay inside for 30 minutes after the last thunder. The first part of the ’30-30 Rule’ has evolved into using hearing thunder to seek a safe place (Roeder, 2007). This change is summarized into the easy to remember slogan. ‘When Thunder Roars, Go Indoors!’. More recently, a complementary slogan for the 30 minute part of the rule was developed, ‘Half An Hour Since Thunder Roars, Now Okay To Go Outdoors!’ These slogans are especially good for teaching lightning safety to children. Other lightning safety training for children is in Hodanish et al. (2008).

In most lightning casualties, the victims were relatively close to a safe location (large proper building or proper vehicle). These people should not use the lightning crouch, rather they should get inside immediately (and practice indoor lightning safety when they get there). The number of lightning casualties in remote places, where the lightning crouch would be used, is relatively small (Holle, 2005a, 2005b). This is also consistent with the author’s anecdotal review of several hundred internet media reports of lightning casualties from around the world since 1998. Also, because the details of when and where and how to use the lightning crouch are so detailed, you can spend far more time teaching it than is justified. Thus, it is not cost-effective to teach outdoor lightning risk reduction, especially when so much of the public still needs training on the basics of lightning safety. Training time is better spent on the first three levels of lighting safety, not this fourth level of desperate last resort, in the hopes of avoiding the need for the final fifth level of first-aid (Lushine et al., 2005).

TABLE 5. Reasons not to teach last minute outdoor lightning safety to the general public.

Weakness	**Repercussion**
Devastating consequences of lightning striking a person	Death or life-long debilitating injuries in many of the cases. Even a risk reduction of about half is not enough.
Fixation on lightning crouch	May lead people to ignore more effective lightning safety procedures.
Over confidence in effectiveness	May lead people to spend too much time under unsafe conditions.
Subtle distinction between outdoor lightning risk reduction and safety	Lightning crouch may undermine credibility of lightning safety training by appearing to contradict fundamental principle that ‘no place outside is safe near a thunderstorm.’
Too complicated	People may misremember, especially under stress, such as when a lightning strike is imminent.
Too complicated	People may misapply, especially under stress, such as when a lightning strike is imminent.
Too complicated	Not cost effective to teach. Takes time away from more effective lightning safety training.
Relatively few lightning casualties in remote locations away from safe place	Not cost-effective to teach. Training time better spent on lightning safety procedures with more impact.

5.2 Reasons To Teach This To The Public

Besides being effective, there is only one reason to teach last minute outdoor lightning risk reduction – customer requirement. Some people spend extended periods away from lightning shelter in at risk locations. However, this author does not believe the need of this relatively small group justifies adding the lightning crouch to education for the general public. However, last minute outdoor lightning risk reduction may be justified for training to sophisticated users and/or special applications with considerable exposure to lightning hazards while outdoors.

6. Summary

Last minute outdoor lightning risk reduction is effective, reducing the probability of a lightning casualty to 47% $\pm$ 7%. Despite that this represents a significant risk reduction, the author recommends that last minute outdoor lightning risk reduction not be taught as part of lightning safety education for the general public. This is due to the devastating consequences of lightning striking a person and several practical problems in education and real world application (Table 5). However, teaching last minute outdoor lightning risk reduction may be appropriate for sophisticated users that spend large amounts of time far away from safe places from lightning.

This recommendation applies only to the ‘last minute’ part of last minute outdoor lightning risk reduction, when threatened by thunderstorms outdoors with no safe place available with little or no lead-time. Other parts of outdoor lightning risk reduction should still be taught, e.g. scheduling outdoor activities to avoid lightning and risky places to avoid if you must be outside when thunderstorms are in the area.

7. Disclaimer

This paper is presented for informational purposes only and no guarantee of lightning safety is stated or implied by the recommended procedures.

8. Acknowledgements

This paper was reviewed by Mr. Holle of Holle Meteorology & Photography, Dr. Cooper, M.D. of the University of Illinois at Chicago, and Mr. Hodanish of the National Weather Service Forecast Office at Pueblo, CO. Reviewing does not imply concurrence with all parts of the paper.

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