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14. Abstract

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Assessing Risk of Significant Injury from Multiple Stimuli Engagements

Eric Benjamin Beier
Jimmy Fleming
Alan Ashworth

Air Force Research Laboratory, 711th Human Performance Wing,
Airmen Systems Directorate, Bioeffects Division, Human Effects Center of Excellence.
4141 Petroleum Road, JBSA Fort Sam Houston, Texas 78234-2644

Abstract

Assessing Risk of Significant Injury (RSI) for a non-lethal weapon (NLW) is a challenging problem. The Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Human Effects Center of Excellence (711 HPW/RHD HECOE) is the research group within the United States of America Department of Defense (DoD) tasked with analyzing data and assessing RSI for new NLW systems. Operational needs from across the US DoD include complicated engagements requiring incapacitating effects over an area; meeting this need sometimes requires the use of multiple devices (more than one of a single device or multiple different devices). Additionally, the US DoD is pursuing new weapons that disperse multiple payloads from a single device or provide multiple insults from a single device. The employment concepts for these new acquisition programs further complicate the assessment of RSI. This paper describes the challenges associated with assessing RSI from engagements involving multiple stimuli, details the additional challenges added by temporal spacing between insults, suggests future research to fill knowledge gaps, and suggests interim solutions to assess RSI from current programs.

1 Introduction

Public perception of nonlethal weapons (NLWs) is often that they can be used against a target without leaving that target with any permanently disabling outcomes. Those involved in the process of developing and fielding NLWs understand that any NLW used against a target has an inherent likelihood of causing permanent and/or significant injury (PI and/or SI). In the USA, NLW are required by Department of Defense Instruction 3200.19(DODI)[3] to " have relatively reversible effects ... and minimize risk of fatalities, permanent injuries, or permanent damage to materiel; however, they shall not be required to have a zero probability of producing these effects in accordance with DoD Directive 3000.3 ". DODI 3200.19 continues, requiring: "Characterization of the human

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effects of NLW shall be conducted during the materiel development process to assess the likelihood of achieving the desired effect(s) and identify RSI [Risk of Significant Injury] for counter-personnel systems, as well as the RSI for collateral damage to humans from countermateriel systems."

RSI is the measure that has been implemented throughout the US DOD to quantify the likelihood of SI to the target. The formal methodology established by the Human Effects Center of Excellence (HECOE) calculates RSI by first determining the likelihood of an injury occurring (P_IO) and then translating that into RSI by multiplying by the likelihood that an injury of that type requires special treatment or results in a permanent injury ($P_HCC > 0$).[4] The composite RSI ($RSI_{composite}$) can then be found by taking the probabilistic sum of the n sources of significant injuries associated with the technology being assessed. This results in the following RSI equation, which result in a composite RSI valuation ($RSI_{composite}$):

$$RSI = P_{IO} * P_{HCC>0} \tag{1}$$

$$RSI_{composite} = 1 - \prod_{i=1}^{n}(1 - RSI_i) \tag{2}$$

where $P_{HCC>0}$ is the probability that the target will need specialized care to recover to pre-engagement condition, or will never recover.

The requirements placed on NLW programs by DODI 3200.19 put the burden of establishing what level of RSI is acceptable on the combat developer, and does not impose a ceiling on what might be considered "too high". The HECOE is established through a memorandum of agreement between the US Air Force and Joint Non-lethal Weapons Directorate to be the "one-stop shop" for NLW programs to provide assessment of effectiveness and predict risk of their new systems on the intended targets. Therefore, one of the most important roles for the HECOE is to help the combat developer to understand the concept of RSI to aid their decisions in choosing meaningful and measurable RSI requirements that meet the operational need being addressed.

2 Modeling

The HECOE utilizes its suite of human effects models called the Human Effects Modeling and Analysis Program (HEMAP) to assess both risk and effectiveness for NLW. For a NLW, the particular modeling software used to assess RSI is dependent on the stimuli applied by the NLW. For traditional blunt impact NLW, such as rubber bullets, the HEMAP's blunt trauma model (ATBM) is usually sufficient to address all potential sources of SI. For directed energy weapons, RSI is often modeled using one or two specialized models, such as probability of causing burn to the skin (BURNSIM) coupled with specialized models for other particularly vulnerable body parts (e.g. retina)

Assessing RSI for NLWs that deliver a single stimulus (e.g., blunt impact NLWs and some directed energy NLWs) is generally straight forward. However, when it comes to NLW with multiple stimuli (e.g. flashbangs), modeling is more difficult. The list of models typically run for flashbang devices is summarized in Table 1.

Model	**Use**
PREMO (Photostress REcovery Model)	Models temporary flashblindness
AUDITORY	Models temporary and permanent hearing loss from impulse noise
BURNSIM	Models second and third degree burn risk to skin
BBHAZ (BroadBand HAZard model)	Models occupational safety thresholds for retinal burn from broadband light
FPIM (Fragment Penetration Injury Model)	Models penetration injury to soft tissue
ATBM (Advanced Total Body Model)	Models blunt trauma injury to the body

Table 1: Models used in the assessment of flashbang NLW.

While the information in this paper is relevant to other NLW, it has been motivated by current flashbang acquisitions programs that intend to affect a target with multiple insults in a single engagement. This paper will focus on the application of the stimuli assessed by models in Table 1 to flashbang NLW. However, it is important to note that these examples can be abstracted to other NLW whose stimuli are spread across an area of effect (AOE).

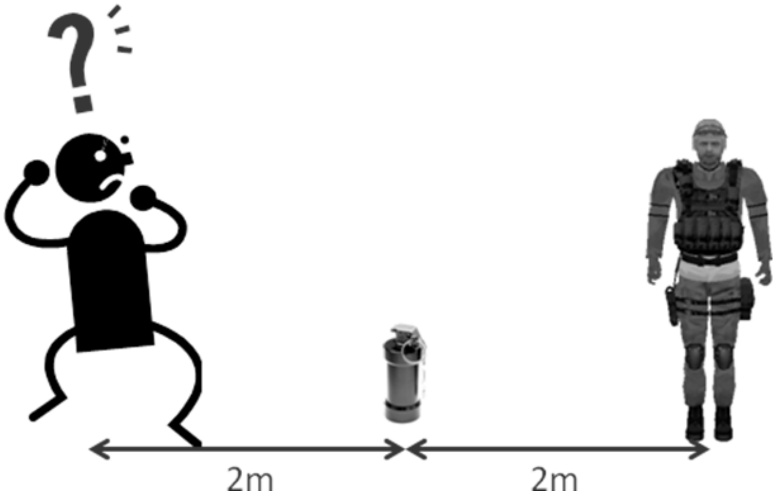
Table 1 includes the models used to predict effectiveness as well as RSI. PREMO and AUDITORY are both used to determine physiological effectiveness of flashbang grenades, but PREMO currently has no direct application in determining RSI. AUDITORY is somewhat of a dual-use model in that it includes dose-response relationships for both temporary threshold shifts (TTS) and permanent threshold shifts (PTS). BURNSIM, BBHAZ, FPIM AND ATBM are all used strictly for RSI calculations. Generally retinal burn risk from broadband spectra flashbang exposures and burn risk to human skin located outside of the fireball itself are zero, so these models are generally run only if the duration or output of the device is atypical.

3 RSI from a Single Source

Calculating RSI from a single flashbang generally follows one of two approaches: a point target approach or an area of effect approach. Assessing against a point target is a straightforward analysis that provides an easily testable metric, but ignores the AOE nature of flashbang devices.

All flashbang devices developed for or acquired by the US DoD since the implementation of DoDI 2300.19 have to include an RSI requirement in their requirements documents. Assessments of earlier flashbang programs (both hand emplaced and tube launched) took a straightforward approach for evaluating RSI. The grenade was assumed to be a fixed distance from the target, and friendly forces were a fixed distance from the target. A notional graphic of this assessment method is seen in Figure 1.

Figure 1: Cartoon depicting single target flashbang assessment. The target (on left) is assumed to be a fixed distance from the flashbang (center) and friendly forces breach the room on the right.



3.1 Application of a Flashbang Against a Single Target

Predicting RSI against a single target requires establishing the location of the target in relation to the flashbang being used. In this “point target” approach, the RSI requirement generally has the following form:

> “RSI will not exceed x% RSI to the targeted individual at y distance from the burst.”

An RSI requirement that applies RSI to a point target ignores the AOE nature of a flashbang grenade. Requirements for flashbang programs initiated prior to the publication of DODI 3200.19 typically followed this type of requirement, as the concept of RSI was new and the models in HEMAP offered limited capabilities. The approach would simply limit RSI to no greater than x% to a single individual y distance from the burst.

For the analyst, this approach has several benefits. First, a single simulation needs to be run for a given output, which means sensitivity analyses on increasing light and sound pressure are straightforward. Operational testing is also easy as the output required to suppress an individual without exceeding the required RSI can be directly measured. However, there are inherent flaws in this approach. Throwing a grenade through a door before breaching the room does not guarantee that the grenade is anywhere near the intended target (reducing effectiveness), or may be closer to the target than intended (increasing RSI). Additionally, the assumptions presuppose a single target in the room, which in many Concepts of Operations (CONOPS) is an unrealistic assumption.

3.2 Application of a Flashbang Over an Area

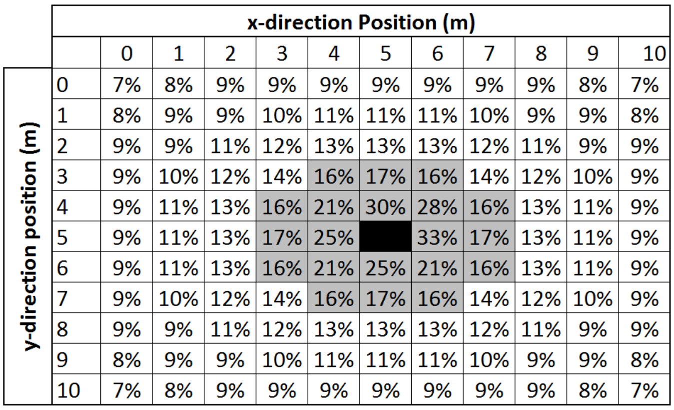
The limitations of treating an AOE NLW as a point target NLW lead the HECOE to develop an AOE approach for flashbang grenades, which was advocated during the 2013 European Nonlethal Weapons Conference [1]. The proposed AOE approach samples over a regular pattern (for example, a grid with 0.5 m intervals between points) and generates an "area of effect" footprint. Separate AOE footprints can be generated for risk and effectiveness; the RSI footprint can then be used to answer requirements regarding RSI over the coverage area. A requirement that lends itself to this type of analysis might take the form:

"The maximum RSI to an individual in the area of effect per flashbang burst shall not exceed $x\%$."

In the above requirement, a number of choices can be made. While it is written as a maximum value, if the CONOPs are written such that limiting average RSI makes more sense, this can be done by defining an area within the AOE and taking the mean of exposure estimates within that area.

One of the strengths of this approach is that it can provide a graphical description of the RSI "hot spots" to the commander or other decision makers. This information can be used to draft tactics, techniques and procedures (TTPs) for given situations, and can help to inform under what situations the RSI associated with a particular NLW is too high.

Figure 2: Composite RSI footprint of a single flashbang grenade. The black square indicates flashbang grenade location. Shaded areas highlight areas with $RSI_{composite} > 15\%$.



y-direction position (m)	x-direction Position (m) 0	1	2	3	4	5	6	7	8	9	10
0	7%	8%	9%	9%	9%	9%	9%	9%	9%	8%	7%
1	8%	9%	9%	10%	11%	11%	11%	10%	9%	9%	8%
2	9%	9%	11%	12%	13%	13%	13%	12%	11%	9%	9%
3	9%	10%	12%	14%	16%	17%	16%	14%	12%	10%	9%
4	9%	11%	13%	16%	21%	30%	28%	16%	13%	11%	9%
5	9%	11%	13%	17%	25%	■	33%	17%	13%	11%	9%
6	9%	11%	13%	16%	21%	25%	21%	16%	13%	11%	9%
7	9%	10%	12%	14%	16%	17%	16%	14%	12%	10%	9%
8	9%	9%	11%	12%	13%	13%	13%	12%	11%	9%	9%
9	8%	9%	9%	10%	11%	11%	11%	10%	9%	9%	8%
10	7%	8%	9%	9%	9%	9%	9%	9%	9%	8%	7%

Applying RSI to the AOE requires detailed information about the scenario(s) in the Concept of Operations to define the type and density of people in the target area (targets and collateral/non-military) and adds a level of complexity to the analysis. The number of individuals in the effected area is important to ensure the space between sampled points in the grid is sufficiently small.

Another level of complexity added to this approach is that accuracy must be figured into the calculation. For example, if a flashbang is designed to burst overhead, RSI increases dramatically if the burst point is 1 m overhead versus 3 m. In model space, this complexity is surmountable, but it can be very difficult to determine RSI if the accuracy requirement is not sufficiently "tight" or is not finalized. This approach was implemented for a recent program in the Department of Defense. Details of the implementation can be found in Beier et al. (2015). [2].

4 RSI from Multiple Sources

When multiple flashbangs are applied in a single engagement, either because TTPs dictate the use of multiple devices or because the NLW is designed to provide multiple insults on target, calculating RSI can become more challenging. In addition to the parameters required in Section 3, locations for each flashbang source must be assumed, either as a fixed “laydown” pattern or defined by a probability distribution.

Whether the flashbang stimuli come from a single device or multiple devices, the challenge becomes how to aggregate the stimuli on each target. For some stimuli (e.g. blunt impactors and fragments), the approach is fairly straightforward: treat each insult to the target independently and take the probabilistic sum. However, for stimuli which affect the target with energies (e.g. sound impulse and directed energy) the occurrence of injury is more complicated because exposure to the first stimuli is more likely to have an effect on the second. (Note that for blunt impact rounds, the assumption of independence may not be valid if multiple insults take place in the same location, but historically each shot has been assessed in the DOD as an independent injury.)

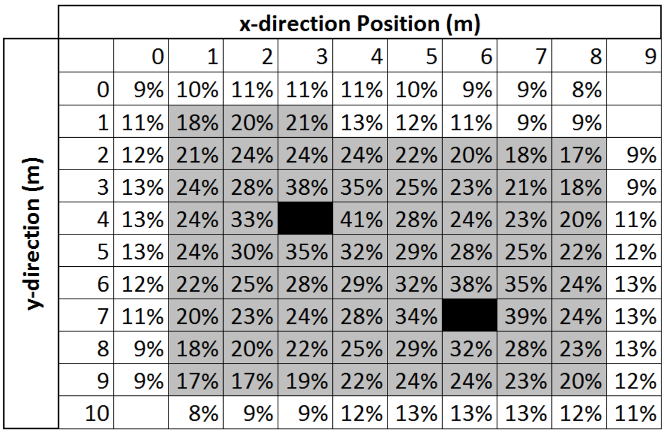
More recently, DoD NLW programs have begun to develop flashbang devices capable of insulting target(s) multiple times per trigger pull. Some devices take the form of a single device with multiple temporally spaced payloads while others disperse several flashbang payloads (which may or may not deflagrate simultaneously). Additionally, some users of fielded NLW grenades have begun asking the question of what happens when multiple devices are thrown into an area.

4.1 Adapting the AOE Approach

In cases where a graphical representation of the RSI associated with a multiple flashbang NLW is desired, an abstraction of the method proposed in Section 3.2 can be used. Generating an AOE footprint for multiple flashbang insults is easier when it is valid to use the assumption that all flashbangs function simultaneously. In general, it can be assumed that all flashbangs occur simultaneously if they all function within a second. A simplistic approach involves generating a human effects footprint as described in Section 3.2 for each functioning flashbang and overlaying them to determine risk. Wherever two footprints overlap, the RSI from each footprint can be combined probabilistically to determine total RSI. However, this approach would not result in an accurate RSI measure for all stimuli produced by a flashbang, in particular for permanent threshold shifts, since the energies from the different flashbangs must be added before determining P_{IO}. The values reported would be conservative from an RSI perspective, but may result in a valuation that exceeds the RSI requirement, increasing program risk.

To eliminate the potential overestimation of RSI described above, energies from each flashbang must be combined before the model is run to convert sound pressure level (SPL) to probability of permanent threshold shift (P_{PTS}). For Auditory (the hearing loss model in HEMAP,) all inputs are assumed to be in A-weighted decibels (dBA). First, the location of each flashbang must be determined and, as in Section 3.2, the area is discretized. For each discrete point, distance to each flashbang is calculated, and the resulting sound pressure (for Auditory, this is in dBA) is determined and summed using

Figure 3: Composite RSI footprint of two flashbang grenades using assumption of independence. Black squares indicate flashbang grenade locations. Shaded areas highlight areas with $RSI_{composite} > 15\%$.



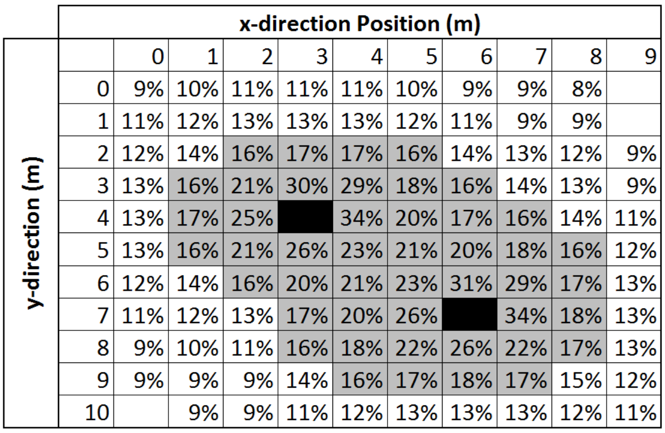
		x-direction Position (m)									
y-direction (m)		0	1	2	3	4	5	6	7	8	9
	0	9%	10%	11%	11%	11%	10%	9%	9%	8%	
	1	11%	18%	20%	21%	13%	12%	11%	9%	9%	
	2	12%	21%	24%	24%	24%	22%	20%	18%	17%	9%
	3	13%	24%	28%	38%	35%	25%	23%	21%	18%	9%
	4	13%	24%	33%	■	41%	28%	24%	23%	20%	11%
	5	13%	24%	30%	35%	32%	29%	28%	25%	22%	12%
	6	12%	22%	25%	28%	29%	32%	38%	35%	24%	13%
	7	11%	20%	23%	24%	28%	34%	■	39%	24%	13%
	8	9%	18%	20%	22%	25%	29%	32%	28%	23%	13%
	9	9%	17%	17%	19%	22%	24%	24%	23%	20%	12%
	10		8%	9%	9%	12%	13%	13%	13%	12%	11%

the following equation:

$$SPL_{combined} = 10log_{10}(10^{\frac{SPL_1}{10}} + 10^{\frac{SPL_2}{10}} ... + 10^{\frac{SPL_n}{10}}) \tag{3}$$

This value is then used as an input into Auditory to determine RSI from PTS. For flashbangs, other sources of RSI (burn, fragment penetration, blunt impact, and retinal burn) can be assumed to be independent injuries, so those insults can be combined probabilistically.

Figure 4: Composite RSI footprint of two flashbang grenades combining dBA energy. Black squares indicate flashbang grenade locations. Shaded areas highlight areas with $RSI_{composite} > 15\%$.



		x-direction Position (m)									
y-direction (m)		0	1	2	3	4	5	6	7	8	9
	0	9%	10%	11%	11%	11%	10%	9%	9%	8%	
	1	11%	12%	13%	13%	13%	12%	11%	9%	9%	
	2	12%	14%	16%	17%	17%	16%	14%	13%	12%	9%
	3	13%	16%	21%	30%	29%	18%	16%	14%	13%	9%
	4	13%	17%	25%	■	34%	20%	17%	16%	14%	11%
	5	13%	16%	21%	26%	23%	21%	20%	18%	16%	12%
	6	12%	14%	16%	20%	21%	23%	31%	29%	17%	13%
	7	11%	12%	13%	17%	20%	26%	■	34%	18%	13%
	8	9%	10%	11%	16%	18%	22%	26%	22%	17%	13%
	9	9%	9%	9%	14%	16%	17%	18%	17%	15%	12%
	10		9%	9%	11%	12%	13%	13%	13%	12%	11%

Note the differences between Figure 3 and Figure 4. When PTS injuries are assumed to have independence, the area of the AOE footprint exceeding 15% RSI increases from $46m^2$ to $65m^2$. Additionally, the maximum RSI observed for this laydown increases from

34% to 41%. With this simple comparison and regardless of the RSI levels chosen, it is not difficult to imagine situations where choosing one analysis approach can lead to a design that fails an RSI requirement while the other passes.

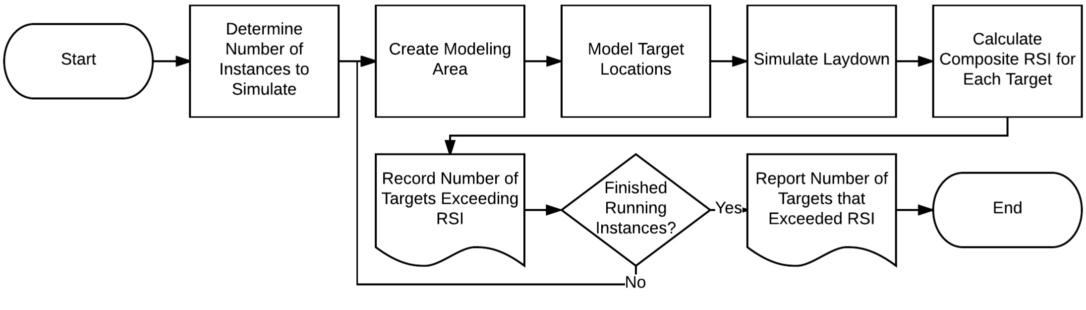
Taking this "brute force" AOE approach comes with a set of drawbacks. Depending upon the design of the NLW, deciding what laydown pattern(s) to model is imperative. The laydown patterns modeled must be representative of what can be expected under normal operating conditions because if they are off by much the RSI calculation may be inaccurate. Further, if the dispersal pattern of the grenades is not very consistent, such as a device that disperses flashbangs from overhead to cover an area with NL effects, then the definition of a few "representative" laydowns becomes unrealistic and the footprint approach becomes computationally intractable under the sheer number of simulations that are required to generate the human effects footprint pictured in Figure 4 for each potential laydown. In this case, a Monte Carlo approach is more appropriate (see Section 4.2).

4.2 Predicting RSI Using a Monte Carlo Approach

Whenever the CONOPs associated with a NLW dictate a scenario where generating an AOE footprint is intractable, determining area RSI requires a new approach. Intractability can occur when the assumption that all flashbangs go off simultaneously cannot be made and/or multiple laydown patterns must be evaluated since the footprint approaches described above treat each point in the vicinity of the stimuli as a target being exposed to the flashbang munitions. The problem then grows exponentially for each laydown pattern and each ordering and timing of flashbang deflagrations. When this is the case, a Monte Carlo simulation approach may become necessary.

To implement a Monte Carlo approach for these type of NLWs, the analyst must first decide how large of an area to simulate. Depending on the program, this may be dictated by the CONOPs being addressed (e.g. on the surface of a naval vessel for boarding operations) or by the design of the device itself (e.g. for devices covering a large area with flashbang grenades.) Then, the number of people and flashbangs being modeled, and probability distributions describing their location must be decided upon. Other parameters to be set include the time between deflagrations and ordering of deflagrations.

Figure 5: Flow chart representing simple Monte Carlo approach for determining RSI for multiple flashbang munitions.



The Monte Carlo approach from this point is fairly straightforward. Using the parameters set above, create an instance to simulate and calculate distances from each target to each flashbang. For penetration and blunt trauma injuries, combining RSIs from each flashbang to each sampled target and assuming independence. If all flashbangs go off simultaneously, then the SPLs can be combined as in Equation 3. If all flashbangs do not go off simultaneously, then the SPLs must be summed another way (this will be discussed in Section 5). Finally composite RSI is calculated using Equation 2. After determining $RSI_{composite}$ for each target, record the number of targets whose RSI exceeded the RSI requirement and iterate through the desired number of instances. Finally, use the recorded RSI outputs to determine whether the flashbang grenade meets or fails the RSI requirement.

5 Modeling Shortfalls

There is currently a gap in the literature involving how to combine multiple auditory insults spread out over time. As discussed previously, if the flashbangs go off nearly simultaneously, then Equation 3 can be used. Otherwise, the limitations of currently available models (AUDITORY) require auditory insults spread over time to be of equal intensity and spaced exactly one second apart. This assumption rarely holds in practice, since even if the flashbangs function one second apart, the fall off of SPL with range results in non-equal SPL values at a target location.

As current NLW programs require RSI valuations using existing models, the HECOE has come up with three interim solutions to evaluate RSI. The first is to simply treat each auditory insult as independent events and sum probabilistically. The resultant value for RSI is extremely conservative (gives a very high value for RSI) and should probably only be used if no other alternatives are available. A second, but still conservative value can be calculated by simply using the SPL addition provided in Equation 3 and then running AUDITORY to predict RSI. This value is conservative because whenever all insults are simultaneous, the protection mechanisms of the ear have not engaged for any of the flashbang insults, so P(PTS) is high. The final option is to determine "sets" of simultaneous flashbang deflagrations (e.g. flashbang set one is all grenades functioning from 0-1 second, set two from 1-2 seconds, etc.) and combine SPLs for each set of flashbangs as described in Equation 3. Then, using either an average of each set (less conservative) or the maximum of each set (more conservative), run the AUDITORY model for these equal intensity insults. This gives a reasonable value for RSI, but does not adequately capture the nature of unequal intensity bursts spread over time. The HECOE is currently working with the Joint Non-lethal Weapons Program (JNLWD) to develop a model capable of combining such insults.

Another knowledge gap in the models and scientific literature is in modeling burn risk from several flashbangs. To date, currently fielded flashbangs have not resulted in a nonzero value for second degree (or deeper) burn risk, but that does not mean that new energetic formulations or the combination of several smaller flashbang grenades could not result in a second degree burn. The literature does not provide a method for modeling the dissipation of energy with range from a flashbang device, which will be important to being able to combine the energies in model space. The HECOE is currently advocating for these modeling tasks.

6 Conclusion

This paper outlines approaches for determining RSI of flashbang grenades that can be generalized to other multiple-stimuli area of effect NLWs. These approaches provide more realistic assessments of the output of flashbang grenades than static point target RSI analyses providing the warfighter more data on the risk associated with applying flashbang technologies currently being fielded and developed. The two main processes advocated are a computationally intensive area of effect footprint and a simple Monte Carlo approach. The paper also points out some limitations in the literature and available modeling capabilities and describes how the HECOE is addressing these modeling gaps.

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