Nerf dart safety and terminal ballistics

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Abstract

Nerf dart safety and terminal ballistics are detailed. Safety case studies are discussed. Common safety rules at Nerf wars are analyzed. Past safety tests are summarized. A parameter called "kinetic energy density" (KED) is introduced to characterize the risk a Nerf dart poses. KED values to cause various injuries are detailed, as are common KED limits in the safety literature. Objective and subjective safety testing are detailed.

1 Introduction

Safety is a paramount issue in Nerf. Most existing safety rules are not based on science, rather, they are based on the subjective experiences of Nerf war organizers. In general, these rules are somewhat uncertain, as they are not based on solid data. Many of these safety rules are too restrictive, banning blasters that pose no safety risk. Some rules are not restrictive enough, banning certain blasters or darts only, opening the door for a new or unfamiliar blaster that is dangerous. Some are outright dangerous, like the policy of one university's HvZ group to test all guns by shooting someone in the eye point-blank [jjj10]. Some are inconsistent, like the common rule that a blaster must be tested by shooting an war organizer or the gun's owner. Such tests are not blinded, leading to placebo pain (i.e., an organizer could complain simply because they *imagine* the gun would hurt). Additionally, people's pain tolerances vary considerably, and a particular gun's owner could be particularly tough, allowing a dangerous gun into play. Thus, there is a need for objective data and tests to inform Nerf dart safety rules.

Most of the traditional terminal and wound ballistics literature is not useful for Nerf. This literature focuses on the ability of bullets to cause death or life-threatening injury and forensics. All those topics are totally foreign to Nerf. Thus, we can not draw on the traditional literature for clues about Nerf dart safety. I draw on a wide variety of data and models from the ballistics and wounding literature.

Non-dart related risks. Darts are not the only safety issue in Nerf wars, but they perhaps are the only unique safety issue. I do not focus on injuries sustained during fabrication or during wars when the cause was not a dart. For example, tripping when running, twisting your ankle, using machine tools in a way that could cause harm, and cutting your hand on poorly sanded plastic, are examples of not uncommon injuries associated with Nerf. These sorts of injuries are avoidable if safety procedures are followed. Proper eye protection and other safety practices when machining are essential, as is being careful during a war. This report examines safety issues posed by darts, as this is where most of the concern lies, regardless of whether or not this concern is misplaced.

Some particular (not immediately obvious) risks posed by Nerf blasters include the risk from barrel tapping with metal barrels, i.e., tapping someone with the end of your barrel as an alternative to shooting them at close range. With metal barrels, this can cut the recipient of the tap. Many risks are also associated with pressurized tanks bursting, and some of these risks are not obvious. Some plastic tanks can produce shrapnel during failure. Less obvious is that the loud noise that can occur when a bladder or pressurized tank bursts can cause hearing loss and tinnitus. Again, these scenarios are beyond the scope of this report.

What does "safety" mean? For the sake of clarity, I think of safety as the state of being certain that negative effects will not occur. Risk is the probability of adverse effects. Zero risk is impossible. All we're doing by designing or using safer darts and implementing safety policies is reducing the probability of injury.

2 Injury case studies

While the overwhelming majority of Nerf dart impacts are safe, as can be verified by attending any Nerf war, numerous impacts that caused injury have been discussed on the internet. To be absolutely clear, it is not my intention in this section to argue that Nerf is an unsafe hobby. The examples I list here are the worst-case, and it'd be a misrepresentation to say that these cherry-picked cases represent what should be expected in Nerf. I also hope my willingness to compile a list of these injuries is seen as evidence that Nerfers take safety seriously and want to improve the already good safety record of the hobby.

Unfortunately, precise data characterizing the dart and gun exist for few of the cases I mention here. I try to fill in the gaps with reasonable guesses when possible. Precise data for a variety of scenarios is described in the KED section.

Finally, for the sake of clarity, I define injury as "any physical damage to the body". This includes minor injuries like welting as well as major injuries such as fractured teeth. I'll also include loss of consciousness under this definition.

Teeth. I am aware of two reports of a Nerf gun knocking a tooth out.

Eyes.

Loss of consciousness. Somewhat surprisingly, in my research I found numerous people who were knocked unconscious by Nerf darts.

Broken bones.

Broken skin.

3 Kinetic energy density

Kinetic energy density, more commonly KED, is a measure of how safe a dart is. KED is defined as follows:

$$T_\mathrm{k}'' \equiv \frac{T_\mathrm{k}}{A_\mathrm{min}}\,, \tag{1}$$

where

T_k'' is the kinetic energy density,

T_k is the dart's kinetic energy, and

A_min is the minimum impact surface area.

For darts where the minimum impact surface area is the projected frontal area of the dart, the following versions of the KED definition can be used:

$$T_\mathrm{k}'' = \frac{\frac{1}{2} m V_\mathrm{m}^2}{\frac{\pi}{4} d^2} = \frac{2m}{\pi}\left(\frac{V_\mathrm{m}}{d}\right)^2 = \frac{4 T_\mathrm{k}}{\pi d^2}\,, \tag{2}$$

where

m is the dart mass,

V_m is the dart muzzle velocity, and

d is the diameter of the dart.

Typical KED values for a variety of stock and modified Nerf guns along with non-Nerf balls are given in table 1.

3.1 Projectile shape effects

Most of the data presented here is for spheres. The impact area of a sphere is smaller than that of something closer to a flat cylinder, like a typical homemade Nerf dart. Thus, these levels may be seen as somewhat conservative. It also could justify a move to spherical nosed homemade Nerf darts, as

3.2 What makes a safe dart? / KED justification

Intuitively, the safety of a dart depends on the dart's mass, the dart's muzzle velocity (the maximum speed the dart will move at unless it is shot down a tall cliff or something similar), the minimum impact area, the hardness of the dart tip, and the thickness of the dart tip. Heavier darts are less safe; they are known to hurt more. Faster darts are known to hurt more. Darts with pointy tips are known to hurt more and can readily penetrate flesh. Harder tips hurt more than soft tips.

The KED formula fits much of our intuition except with regard to tip softness. KED says nothing about the softness of the tip. A different dynamic analysis must be used in that case to account for the extra KED the dart can have while maintaining the same transmitted KED.

The concept of KED was first described by Journée [Jou07]. A mathematical derivation of the KED is given in §3.3.9.

3.2.1 Why not force or momentum?

I often am asked why energy is the right metric and not force or momentum. You could formulate your own safety criteria in terms of force or momentum if you like either better. There would be a few problems going either route, however.

In terms of force, recognize that the impact force varies in time. In discussing this issue with several people, I see that they hold the misconception that there is one constant force during the impact. This is wrong. The force increases as the dart moves into its target because the target acts like a spring. Still, let's consider the worst case scenario and look only at the maximum force. Even the maximum force presents problems. How do you go from dart characteristics (like muzzle velocity, mass, and diameter) and target characteristics (like modulus of elasticity, etc.) to maximum force? Basically, if you do the math, you'd find that the maximum force is related to the kinetic energy of the dart.

As for momentum, again, you could do the math this way, but you'd need t

3.3 KED limits

Risk functions give the probability of causing damage or injury for a particular impact scenario as a function of KED. For example, a risk function for breaking skin would give you the probability that you break skin from a dart impact as a function of KED. A *critical KED value* is the KED value where the probability of damaging something is 50%. Critical KED values are given the notation T''_{crit}.

All values for damaging the human body detailed below should be thought of as estimates. Use generous safety factors and choose low-risk KED limits. This information is provided to put the power of a Nerf gun into perspective so that this power may be fully respected. I do not intend to give the impression

	dart type	m (g)	d_{tip} (inch)	V_{m} (ft/s)	T''_{k} (mJ/mm^2)	source
Longshot (stock)	CSD	1.34†	0.465†	55	1.3	[Ner10]
Recon (stock)	CSD	1.34†	0.465†	50	1.1	[Ner10]
Vulcan (stock)	sonic micros	1.5	0.465	34	0.74	[All11]
Nitefinder (stock, original)	sonic micros	1.5	0.465	50	1.6	[jer11]
Retaliator (stock, no barrel ext.)	Elite streamlines	1.0	0.465	75	2.4	[Foa13]
Retaliator (stock, barrel ext.)	Elite streamlines	1.0	0.465	69	2.0	[Foa13]
Firestrike (stock)	Elite streamlines	1.0	0.465	74	2.3	[Foa13]
Rough Cut 2x4 (stock)	Elite streamlines	1.0	0.465	61	1.6	[Foa13]
Triad EX-3 (stock)	Elite streamlines	1.0	0.465	61	1.6	[Foa13]
Strongarm (stock)	Elite streamlines	1.0	0.465	65	1.8	[Foa13]
Alpha Trooper CS-12 (stock)	Elite streamlines	1.0	0.465	61	1.6	[Foa13]
Stryfe (stock)	Elite streamlines	1.0	0.465	64	1.7	[Foa13]
Hammershot (stock)	Elite streamlines	1.0	0.465	66	1.8	[Foa13]
Magstrike (stock)	Elite streamlines	1.0	0.465	61	1.6	[Foa13]
JT Splatmaster Z100 (stock)	Elite streamlines	1.0	0.465	128	6.9	[tor14]
Modified Recon	CSD	1.34†	0.465†	80	2.8	[Ner10]
Modified Recon	CSD	1.34†	0.465†	96	4.0	[Ner10]
Modified Longshot	CSD	1.34†	0.465†	132	7.6	[Ner10]
Brass Breech Longshot	CSD	1.34†	0.465†	210	19	[Ner10]
Brass Breech Recon	CSD	1.34†	0.465†	108	5.1	[Ner10]
3B (k26 and perfect seal)	#6 washer slugs	1.0	0.53	175	10	[Bea10]
SNAP 5 with hopper	#6 washer slugs	1.0	0.53	190	12	[Bea10]
SNAP 2 with hopper	#6 washer slugs	1.0	0.53	200	13	[Bea10]
PAC with hopper	#6 washer slugs	1.0	0.53	200	13	[Bea10]
Singled +bow	#6 washer slugs	1.0	0.53	210	14	[Bea10]
Modified SM 1500	#6 washer slugs	1.0	0.53	250	20	[Bea10]
Modified Big Blast	#6 washer slugs	1.0	0.53	350	40	[Bea10]
Crossbow with brass barrel	stefans	0.7	0.53	200	9.1	[mad09]
Singled Titan	stefans	1.2†	0.53	365	52	[Jab06]
Modified Nitefinder	stefans	1.2†	0.53	72	2.0	[Jab06]
Singled SM5K	stefans	1.2†	0.53	282	31	[Jab06]
Doomsayer (weak spring)	stefans	1.18	0.53	108	4.5	[Foa14]
Strongarm (AR removed)	Elite streamlines	1.0	0.465	74	2.3	[tor14]
Alpha Trooper CS-12 (AR removed)	Elite streamlines	1.0	0.465	74	2.3	[tor14]
Triad EX-3 (stronger spring)	Elite streamlines	1.0	0.465	83	2.9	[tor14]
Retaliator (no barrel ext., etc.*)	Elite streamlines	1.0	0.465	112	5.3	[tor14]
Retaliator (barrel ext., etc.*)	Elite streamlines	1.0	0.465	95	3.8	[tor14]
RapidStrike CS-18 (modified)	Elite streamlines	1.0	0.465	109	5.1	[tor14]
ping pong ball	—	2.5	0.59*	147	14	[SS89]
paintball (at common safety limit)	—	2.5	0.68	280	66	[DD04]
airsoft (at common safety limit)	—	0.2	0.24	350	40	[Wik14a]
tennis ball	—	57	2.63	160	20	[tea01; Ele00]
lacrosse ball (fast)	—	147	2.47	147	48	[Wik14c]
golf ball (average golfer)	—	45.93	1.68	195	57	[Wik14b; Tra14]

Table 1: Typical KED values for different blasters and non-Nerf items.

† This value is a possibly poor guess.

* This is the impact diameter, not the ball diameter.

* Air restrictor removed, stronger spring.

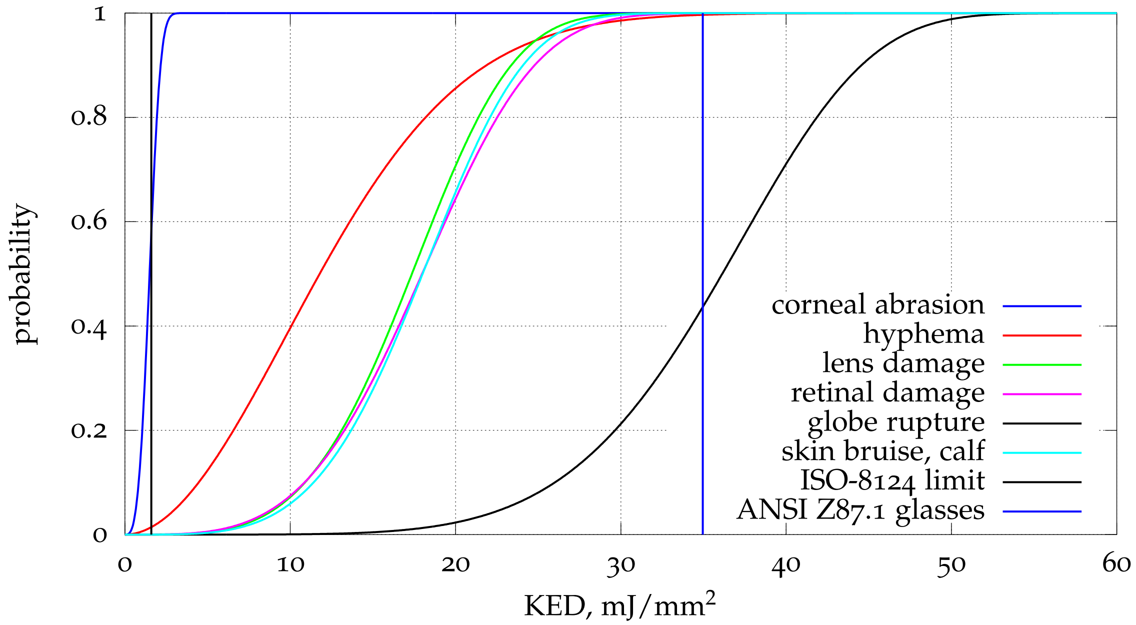

Figure 1: Probabilities of various injuries from projectile impact as a function of KED.

that damaging the body is difficult in Nerf, in fact, I want to give the opposite impression so that we can improve safety in this hobby.

3.3.1 Toy standards

Hasbro's SRS-045 [Fis99] sets a KED limit of 1.6 mJ/mm^2 for projectiles with a KE over 80 mJ. This limitation is based on ISO #8124, specifically section 4.18 [Bli10; Int09]. Hasbro usually designs for 20% under this limit to account for manufacturing variations [Bli05]. Despite this, as seen in table 1, several Nerf blasters released by Hasbro appear to have KEDs higher than 1.6 mJ/mm^2 when tested.

3.3.2 Eye injury

Eye injury is possibly the worst injury one could suffer from a Nerf dart. Additionally, eye injury is the best studied of all the injuries detailed here. Risk functions for a variety of different types of eye injuries have been developed [KD11]. These functions include:

- corneal abrasion — scratching the cornea
- hyphema —
- lens damage —
- retinal damage —
- globe rupture —

These risk functions (and others) are plotted in figure 1. Computed probabilities of injury from these risk functions including the critical KED value (50% probability) are listed in table 2.

The risk functions themselves are of the form

$$P_{\text{injury}}(T_{\text{k}}'') = 1 - \exp\left[-\left(\frac{T_{\text{k}}''}{\alpha}\right)^{\beta}\right] , \tag{3}$$

	0.1%	1%	5%	10%	25%	50%	75%	90%	95%	99%	99.9%
corneal abrasion	0.20	0.40	0.67	0.83	1.1	1.5	1.8	2.2	2.3	2.7	3.0
hyphema	0.40	1.3	3.1	4.5	7.5	11.8	16.8	21.9	25.1	31.3	38.5
lens damage	3.4	6.1	9.1	10.9	14.0	17.4	20.6	23.4	24.9	27.7	30.7
retinal damage	3.1	5.8	9.0	10.9	14.2	18.0	21.6	24.8	26.6	29.8	33.2
globe rupture	11.5	17.3	22.9	26.0	31.0	36.1	40.8	44.6	46.6	50.3	54.0
bruising	3.7	6.5	9.6	11.4	14.6	18.0	21.3	24.1	25.7	28.5	31.4
breaking skin	33.4	59.5	89.5	107.2	137.9	171.9	204.5	232.2	248.0	276.3	305.8
breaking bone						~200					

Table 2: KED values in $\mathrm{mJ/mm^2}$ for certain levels of risk.

	α ($\mathrm{mJ/mm^2}$)	β
corneal abrasion	1.67	3.23
hyphema	14.23	1.94
lens damage	19.01	4.04
retinal damage	19.83	3.74
globe rupture	38.52	5.73
bruising	19.68	4.13
breaking skin	188.4	3.99

Table 3: KED risk function parameters.

where α and β are model constants that change for each scenario. These are given for a variety of different scenarios in table 3.

3.3.3 Bruising and welting

Welting occurs before bruising. There is little hard data available on welts. What is certain is that welts occur before bruising. Based on some small tests ($N = 2$) performed by catbarf at the HvZ forums [cat12], a KED of about $12\,\mathrm{mJ/mm^2}$ will cause welting. This is definitely not the minimum value, as carbarf only did two shots, both of which had approximately the same muzzle velocity, and both of which caused welts to appear.

There is some limited data on bruising. Desmoulin and Anderson [DA11] did some simple tests that can be used to find an approximate risk function for bruising. Unfortunately, they only tested one person and only had 6 data points, so the risk function is very approximate, but it is the best that can be constructed with the available data. This risk function is graphed in figure 1. There are tabulated values of this risk function in table 2 and the coefficients of the risk function used are listed in table 3.

The risk function for bruising is very close to those for lens damage and retinal damage, as can be see in figure 1. Thus, it appears that bruising is a good proxy for whether a Nerf gun could cause significant damage to unprotected eyes, as others had suspected in the past.

3.3.4 Breaking skin

Sellier and Kneubuehl [SK94, p. 222] analyze multiple sources and suggest an average critical KED value of about $175\,\mathrm{mJ/mm^2}$. DiMaio et al. [DiM+82] provide data that can be used to construct a risk function.

Their data suggests a critical KED value of $172\,\mathrm{mJ/mm^2}$, which is consistent with others' data. As before, this risk function is tabulated in table 2 and the coefficients of the risk function in table 3.

These values are for skin penetration (i.e., breaking or becoming embedded in the skin), not bruising or welting. As discussed prior to this section, bruising and welting occur are far lower KED values.

3.3.5 Tooth damage

3.3.6 Breaking bone

Data summarized by Sellier and Kneubuehl [SK94, p. 231] leads to an average critical KED value of about $200\,\mathrm{mJ/mm^2}$. Sellier and Kneubuehl [SK94, p. 231] also suggest that a critical KED limit does not fit the data well for bone, and rather a critical velocity of about $60\,\mathrm{m/s}$ fits the data better.

3.3.7 Loss of consciousness

3.3.8 Impact rated glasses

3.3.9 Damage to general material

Denting metals. The material can be assumed to deformed in a simple manner as a simplification: the projection of the impact area deforms like a linear spring and nothing else deforms [Bei08]. This basic scenario is demonstrated in figure 2.

At the moment of impact, the surface and the dart move forward as one. If the mass of the part of the surface that is moving is far lower than the mass of the dart, then that mass can be ignored in the calculation.

How much energy per unit volume can a material absorb before permanently deforming (i.e., denting, or yielding as it's called to engineers)? This energy is called U_r, the modulus of resilience if the linear spring model is used. If the impact area multiplied by the thickness (the minimum amount of material involved in the impact) multiplied by the modulus of resilience is larger than the kinetic energy of the projectile, the projectile is fully defeated; the target will not even be dented.

This energy can be found with Hooke's law and the work-energy theorem (the latter after being normalized per unit volume). σ_y is the yield stress and ε_y is the yield strain,

$$W = \int F dx \longrightarrow \underbrace{\frac{W}{L^3}}_{W'''} = \int \underbrace{\frac{F}{L^2}}_{\sigma} \underbrace{\frac{dx}{L}}_{d\,\varepsilon} \longrightarrow W''' = \int \sigma d\,\varepsilon \tag{4}$$

$$\sigma = E\varepsilon \tag{5}$$

$$U_\mathrm{r} = \int_0^{\varepsilon_\mathrm{y}} \sigma d\,\varepsilon = \int_0^{\frac{\sigma_\mathrm{y}}{E}} E\varepsilon d\,\varepsilon = \left[\frac{E\varepsilon^2}{2}\right]_0^{\frac{\sigma_\mathrm{y}}{E}} = \frac{\sigma_\mathrm{y}^2}{2E} \tag{6}$$

This material property can be multiplied by the thickness of the material to find a critical KED value for that material for yielding.

$$T''_\mathrm{k,crit} = U_\mathrm{r} t = \frac{t\sigma_\mathrm{y}^2}{2E} \tag{7}$$

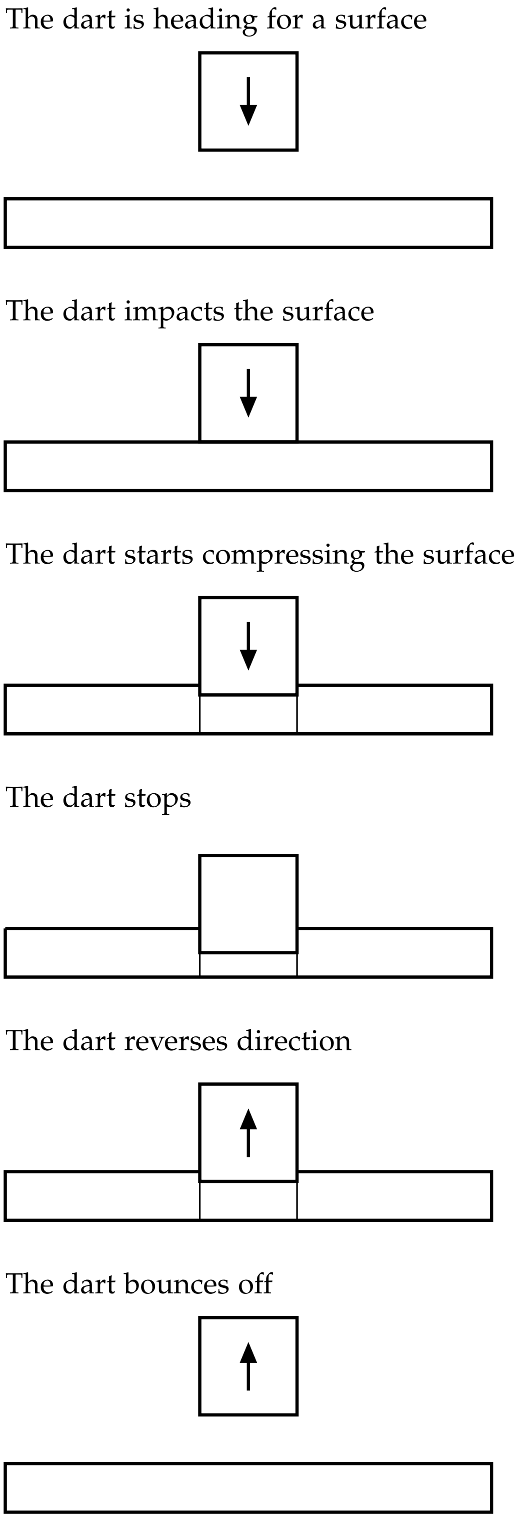

Figure 2: Dart impact modeled as a simple linear spring. Boxed area is the area under stress. No other area experiences stress in this model.

Note that yielding really only is denting; if the KED value is less than the critical KED value, the material will completely defeat the projectile without any denting (unless fatigue is considered). This information can be directly used to determine whether eye-wear will protect against a dart.

Material penetration. If the KED value is greater than the critical KED value, all that can be said is that at least the material will be slightly dented. Potentially the projectile could dent or fracture the target and bounce off. Potentially the projectile could be embedded in the target. Potentially the projectile could pass completely through the sheet. This analysis offers little indication about which is more likely. Sellier and Kneubuehl [SK94] have some information about projectiles moving through objects they impact.

Material defeat. Different critical KED values for complete defeat of the material (i.e., shooting through a material) can be found most accurately experimentally or via finite element analysis. Very rough estimates can be found from analysis similar to that for the linear elastic case. The difference is that instead of just integrating the strain out to the yielding point, you integrate out to the ultimate point.

Future directions. The data for welting and bruising is inadequate. Future tests to determine what KED values will welt and bruise would be very worthwhile and not difficult to do for someone with an airgun (such that the power can be widely varied), a small scale, and a chronograph.

3.3.10 Notes

A note for the squeamish. Most of the references containing critical KED data also have photographs of gunshot wounds that some readers may find to be disturbing. Don't look at these references if you are squeamish.

Why do serious eye injuries appear to be rare in the NIC and HvZ? Given how little energy is required for serious eye damage, I'm not entirely sure why serious eye injuries are so rare. I'd guess that it's a combination of the eyes having very little surface area, a lot of folks wearing (seeing) glasses or impact-rated eye protection, people trying to avoid head shots, that most eye shots are probably not direct, and that most shots are at a distance, so that darts lose energy to drag. The eye tests represent the worst-case scenario, as they are point-blank direct shots at the eyes.

Other notations. Sellier and Kneubuehl [SK94] use E'_{ths} for the critical kinetic energy density. "ths" refers to a threshold; this is the threshold to start penetrating something. This notation's use of a prime does not make sense as the primes in this context generally denote normalization with respect to one length. Two primes are necessary for normalization with respect to an area (i.e., a length squared).

3.4 Effect of soft tips on darts

3.4.1 Effect of soft tips (elasticity)

Soft-tip (elastic) darts are known to hurt less than hard tipped darts. The reason is that energy is absorbed in the tip during impact as well. The actual transfered energy to the target is what matters, and that value is not the same as the dart KED. I call this transfered energy "transfered KED" to distinguish it from the actual KED of the dart.

Note that the simple analysis I do here is very approximate, and serves mainly to gain an understanding of what factors affect dart safety. Experimental testing of soft dart tips in combination with a knowledge of the factors involved would be best. The material penetration test in section 4 would be well suited to find the effective (transfered) KED value of a dart. Essentially, you use the thickness of material the dart will defeat to estimate the kinetic energy transferred to the target material. This will be lower than the kinetic energy of the dart. The difference is absorbed by the soft tip. This soft-tip (transfered) KED value is the actual relevant value.

The dart impact can be modeled as a spring-mass system. The mass is assumed to only be the dart mass, which makes this analysis conservative as the displacement of the target will be greater if the mass is lower. This analysis can be modified to include the effect of the target mass if you believe it is important in your case. The equation of motion (with dart mass m and spring constant k) is

$$m\ddot{x} + kx = 0\,, \tag{8}$$

where x is the displacement of the dart into the target. The solution to this differential equation is

$$x(t) = V_\mathrm{m}\sqrt{\frac{m}{k}}\sin\left(\sqrt{\frac{k}{m}}\,t\right)\,. \tag{9}$$

You can see that the maximum displacement the dart will undergo is $x_\mathrm{max} = V_\mathrm{m}\sqrt{m/k}$ because sin reaches a maximum of 1. The force is $F = kx$ in this case, and the stress in the material is $\sigma = F/A_\mathrm{min}$ where A_min is the impact area as defined before. From there you can find the maximum stress of the target during impact:

$$\sigma_\mathrm{max} = \frac{kV_\mathrm{m}\sqrt{m/k}}{A_\mathrm{min}} = \frac{V_\mathrm{m}\sqrt{mk}}{A_\mathrm{min}}\,. \tag{10}$$

This equation can be rearranged to find the (hard-tip) KED of the dart:

$$\frac{\sigma^2_\mathrm{max}A_\mathrm{min}}{k} = \frac{V^2_\mathrm{m}m}{A_\mathrm{min}} \longrightarrow \frac{\frac{1}{2}mV^2_\mathrm{m}}{A_\mathrm{min}} = T''_\mathrm{k} = \frac{\sigma^2_\mathrm{max}A_\mathrm{min}}{2k}\,. \tag{11}$$

T''_k is the KED (i.e., actual kinetic energy density) of the dart. Now the effective spring constant must be calculated. Noting that for two springs in series $1/k = 1/k_\mathrm{t} + 1/k_\mathrm{d}$ where t refers to the target material and d refers to the dart. Using that and spring constant for a solid linear elastic material ($k = EA/L$) results in

$$T''_\mathrm{k} = T''_\mathrm{k} = \frac{\sigma^2_\mathrm{max}A_\mathrm{min}}{2}\left(\frac{t_\mathrm{t}}{E_\mathrm{t}A_\mathrm{min}} + \frac{t_\mathrm{d}}{E_\mathrm{d}A_\mathrm{min}}\right) = \underbrace{\frac{\sigma^2_\mathrm{max}t_\mathrm{t}}{2E_\mathrm{t}}}_{\text{absorbed by target}} + \underbrace{\frac{\sigma^2_\mathrm{max}t_\mathrm{d}}{2E_\mathrm{d}}}_{\text{absorbed by dart tip}}\,. \tag{12}$$

The KED is broken into two parts: one absorbed by the target, and one absorbed by the dart tip. The dart tip thickness is t_d and the target thickness is t_t. Similarly, the dart tip modulus of elasticity is E_d and the target modulus of elasticity is E_t. Note that the term that represents the KED absorbed by the target is exactly the same as eqn. 7; this how you know it is the absorbed KED.

Given this result, you can find a KED limit for soft-tipped darts ($T''_\mathrm{k,dart,max}$) for an existing KED limit that used hard projectiles ($T''_\mathrm{k,hard,max}$):

$$T''_\mathrm{k,dart,max} = T''_\mathrm{k,hard,max} + \frac{\sigma^2_\mathrm{max}t_\mathrm{d}}{2E_\mathrm{d}}\,. \tag{13}$$

From this result, you can see that using softer dart tips (lower E_d) and increasing the dart thickness (t_d) always increases the allowable KED. The effect of dart tip thickness is shown in figure 3.

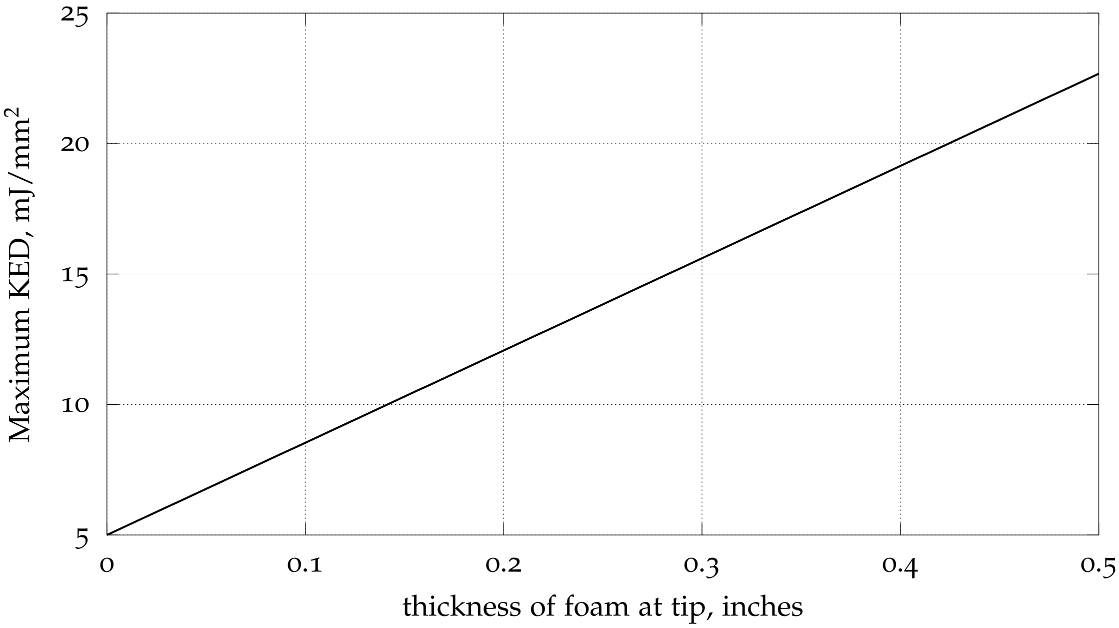

Figure 3: Maximum allowed KED for a hypothetical hard-tip/transfered KED limit of 5 mJ/mm^2 .

The notation $T''_{\text{k,hard,max}}$ is used for the KED limits mentioned previously because the tests to find those limits had hard projectiles. Those KED limits are the "hard-tip" limits.

A similar analysis can be done to include the effects of internal friction (damping) in the dart tip. My own analysis has indicated this effect is fairly negligible for Nerf darts, and thus it is not included in this report.

3.5 Metal-free darts

4 Safety testing

4.1 Objective testing

Chronograph, scale, and calipers. A chronograph, a small scale, and potentially some calipers can be used to find KED. Measure the muzzle velocity of the blaster, the mass of the dart, and the diameter of the dart. These numbers can be directly plugged into the KED equation.

Ballistic pendulum. A ballistic pendulum can be used to directly find the kinetic energy of the dart, and from there the KED can be found by dividing the KE by the minimum area. A ballistic pendulum is far easier to build than a homemade chronograph, as it only involves a pendulum and some weighted target for the projectile. A styrofoam target should work nicely for Nerf applications.

Material penetration. Using the information in the "Damage to material" section above, one can figure out what thickness of a certain material is necessary to dent it. Practically speaking, however, this is not useful as denting any material a Nerf gun could easily shoot through like cardboard is very simple.

Empirical testing with a sheet of cardboard, aluminum foil, or something similar can find the KED necessary to penetrate the sheet, and this sheet can then be used to test whether the KED of a blaster is below or above a certain limit.

4.2 Subjective tests

5 Suggestions for Nerfers

Special thanks

Special thanks to Blood Angel at NerfHaven for some useful discussions by private message which improved the quality of this report. I'd also like to thank torukmatko4 for catching mistakes in the table of KED values for different blasters.

Future directions

I have a few planned sections for this document:

- a section on the effect of material damping, that is, energy converted to heat due to internal friction.
- a section analyzing Nerf gun safety data from NEISS, a database of product injury reports.
- a section analyzing the effect of clothing on KED limits (clothing increases the KED limit for skin).
- a table listing the hardnesses, mass density, etc., of various dart materials and body parts, along with information about how to convert common hardness measures to useful forms.
- subjective dart pain tests that were properly blinded to get a better idea of what people find painful.
- a section analyzing common safety rules at Nerf wars.
- results from some dart safety tests Daniel Beaver and koree did.

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