



Original Contribution

Eye injury from electrical weapon probes: Mechanisms and treatment



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ABSTRACT

Purpose: While generally reducing morbidity and mortality, TASER® electrical weapons have risks associated with their usage, including burn injuries and head and cervical trauma associated with uncontrolled falls. The primary non-fatal complications appear to be significant eye injury but no analysis of the mechanisms or suggested treatments has been published.

Methods: We used a biomechanical model to predict the risk of eye injury as a function of distance from the weapon muzzle to the eye. We compared our model results to recently published epidemiological findings. We also describe the typical presentation and suggest treatment options.

Results: The globe rupture model predicted that a globe rupture can be expected (50% risk) when the eye is within 6 m of the muzzle and decreases rapidly beyond that. This critical distance is 9 m for lens and retinal damage which is approximately the range of the most common probe cartridges. Beyond 9 m, hyphema is expected along with a perforation by the dart portion of the probe. Our prediction of globe rupture out to 6 m (out of a typical range of 9 m) is consistent with the published risk of enucleation or unilateral blindness being $69 \pm 18\%$, with an eye penetration.

Conclusions: Significant eye injury is expected from a penetration by an electrical weapon probe at close range. The risk decreases rapidly at extended distances from the muzzle. Not all penetrating globe injuries from electrical weapon probes will result in blindness.

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1. Introduction

Electronic control with the CEW (conducted electrical weapon) has gained widespread acceptance with law-enforcement, as the preferred less-lethal force option due to its dramatic injury reduction compared to other control tools. Large prospective studies have found reductions in the subject injury rate of about 65% [1]. Of the 310,000 annual CEW field uses, 1 in 3500 is involved in a non-firearm ARD (arrest-related death) vs. the baseline ARD rate of 1:1000 [2]. This is consistent with a 2/3 reduction in fatal police shootings where CEW usage is not overly restricted [3].

Electrical weapons are, after all, weapons, and there are indeed risks associated with their usage, including fatalities from falls and burns [4-

6]. They launch probes with darts and hence there is a risk of significant eye injury. See Fig. 1. The risk of penetrating eye injury has been recently reported as 1:123,000 confidence limits [85,000, 178,000] by Wilson score interval [7]. The goal of this paper is to analyze the risks of such injury from an analytical framework and to provide guidelines for emergent care.

A CEW has both laser and fixed sights. The X26E CEW series has a single laser that approximately aligns with the top dart. The lower probe is launched at a separation angle of 8° below the laser line. Newer models such as the X2 have dual laser sights and a separation angle of 7°. To obtain a high level of motor-nerve mediated neuromuscular incapacitation – on the front of the body – there must be a probe separation of at least 30 cm (12 in) [8]. This requirement, of a large spread, adds to a risk of a facial impact – especially if the subject ducks to avoid the probes.

The critical range for a devastating eye injury such as a globe rupture has not been established. The optimal therapy for a CEW probe injury has also not been published.

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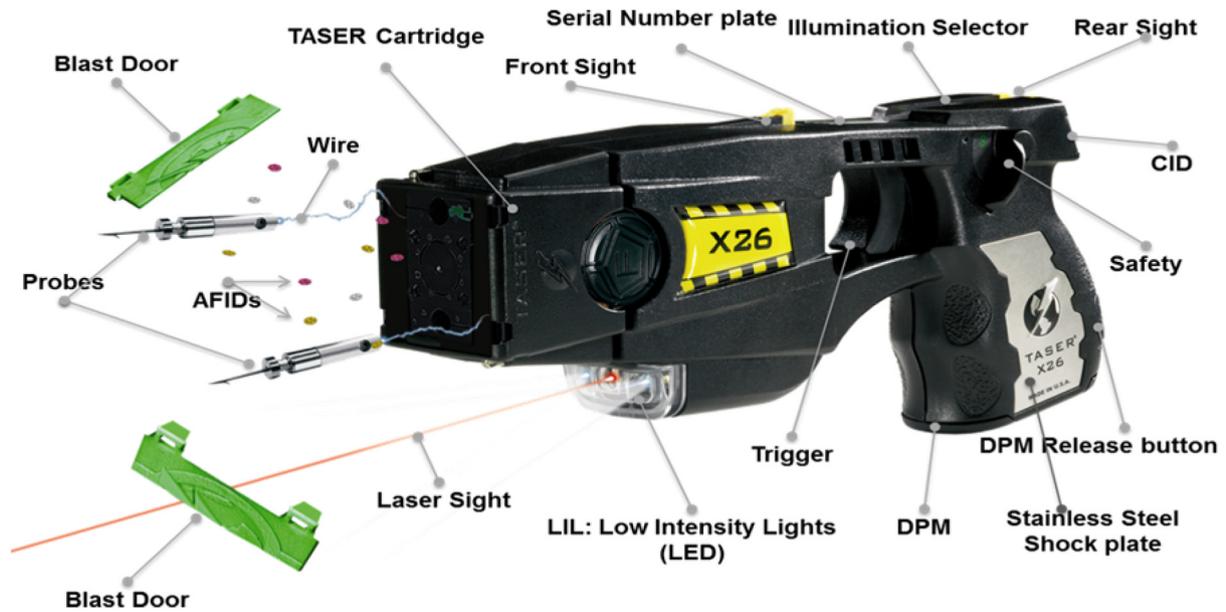


Fig. 1. X26(E) CEW during probe deployment.

2. Methods

The prediction of eye injuries from ballistic impact has been studied by: (1) finite-element simulations that investigate tissue-level mechanical response from an impact, and (2) empirical models that correlate injury outcome to projectile ballistics. The simulations have proven useful in the investigation of potential mechanisms for different injury outcomes [9–11]. The empirical models have highlighted the significance of 3 parameters for eye injury risk: (1) projectile mass, (2) projectile velocity, and (3) projectile size [12–15]. These 3 parameters can be combined to simply calculate the energy density or ANE (area-normalized energy) in kJ/m^2 , which is the kinetic energy of the projectile divided by the projectile's cross-sectional area [15]. The ANE was shown to predict eye injury with logistic regression analysis [12,14].

Comprehensive risk functions have been derived from experimental eye impact tests using post-mortem human eyes, live animal surrogates, and post-mortem animal eyes [9,11–17]. The predictions, using a logistic transformation of the ANE, have been validated for recreational weapons such as airsoft pellet and paintball guns [9,13]. These risk functions have also been validated over a broad range of small projectiles of various velocities, and have been compared against predicted corneo-scleral stresses and internal eye pressure from matched computational simulations [11,16].

These risk functions have been based on spherical and blunt cylindrical objects ranging in diameter from 4.4 mm to 19.9 mm. The CEW probe diameter (5.5 mm) falls in between BBs (4.4 mm) and airsoft pellets (6.0 mm). Overall, the energy profiles of the objects were very similar. The BB velocities range from 115 to 145 m/s and the ballistic energy ranges from 2.2–3.6 J, compared to the 2.6 J of the CEW probe at the muzzle. The ANE of BBs ranges from 145 to 235 kJ/m^2 , compared to the 112 kJ/m^2 initial value for the CEW probe.

The dart (tip) of the probe will markedly increase the chance of a penetrating eye injury, therefore, the risk functions are not to be interpreted as an indicator of dart induced injuries (e.g. they cannot predict the risk of penetrating injuries as a result of a direct hit by the probe-tip per se). For the CEW probe, we applied these injury functions by assuming that the sharp “dart” portion (of the probe) will *always* penetrate the globe and hence that is not part of the modeling (see Fig. 2). Depending on where the dart penetrates, the injuries (from the dart portion, per se) are typically pin-hole defects or blurring. There have been cases of globe rupture where the dart-tip

lodged in posterior structures and thus presumably effected other damage.

The models predict 4 different types of eye injury: (1) hyphema, (2) retinal damage, (3) lens damage, and (4) globe rupture. This modeling is based only on the impact of the shoulders of the main part of the probe. Hyphema will occur first with a centered impact. With greater impact energy, this is followed by both lens and retinal damage which have similar thresholds. The lens damage is due to the local mechanical stresses. The retinal damage is hypothesized to be due to: (1) high globe deformation and localized stresses causing tissue failure, or (2) contrecoup injury due to pressure shock transmission. Finally, the globe rupture occurs when tensile stress thresholds (particularly in the corneo-scleral shell) are exceeded.

The X26E CEW probe is shown in Fig. 2. The probe ballistics (mass 2.85 g, diameter 5.4 mm), were utilized to calculate the kinetic energy and density (ANE) from the muzzle (0 m distance) to 10.67 m. The initial probe velocity and energy of 42.7 m/s (2.6 J) decreases to 10.7 m/s (0.2 J) at ~11 m. The ANE (kJ/m^2) was utilized to calculate the risk of eye injury (hyphema, retinal damage, lens damage, and globe rupture) based on the logistic injury risk functions of Duma and Kennedy [12,14]. The ANE, relative to flight distance, is plotted in Fig. 3.



Fig. 2. Single-shot probe as used in X26 models. Dart portion is 13 mm long; other version has 9 mm dart.

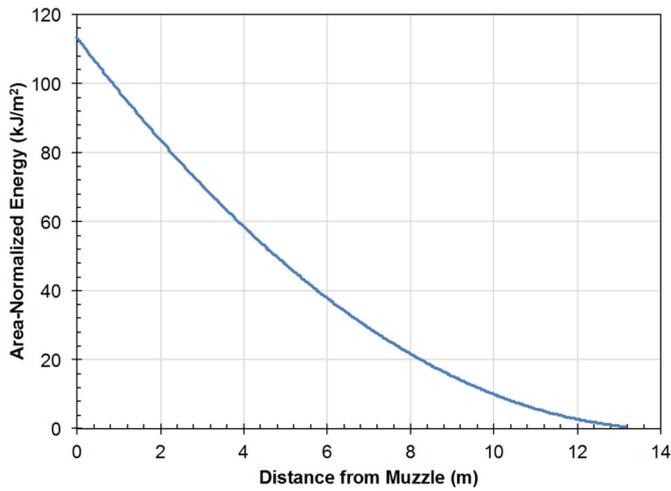


Fig. 3. Area-normalized energy (energy density) of an X26E CEW standard probe.

3. Results

This area-normalized energy was used to calculate the risk of the 4 eye injuries as a function of distance as shown in Fig. 4. These risk functions predict a 50% risk of a globe rupture at distances <6.2 m. The threshold distance for retinal and lens damage is 8.6 m; for hyphema the threshold is 9.6 m. With a preferred muzzle-to-subject targeting range of 2.1–4.6 m (7–15 ft.) each of these thresholds is within the preferred range and hence a subset of these injuries are expected in a typical probe deployment with eye contact.

It should be noted that these injury-risk curves represent the risk of a “perfectly” errant probe deployment, where the eye is struck directly at a perpendicular angle in the center and there is no eyelid absorbing probe energy. The modeling – and all of the cases listed below – is for the M26 and X26E models. Newer models (e.g. X2 and T7) have different probes.

The effects of longer-distance (lower impact energy) probe landings are significantly different. In that case, the “specific energy” is lower so that the impact of the probe “shoulder” is not the primary factor in the eye injury (along with hyphema from the impact of the probe shoulder). Depending on the landing location, the sharp “dart” portion will penetrate and may cause only acute damage, blurring, or a pinhole defect. However, if the dart penetrates the lens regardless of shoulder impact then we would expect more clinically significant injury than, say, mere hyphema.

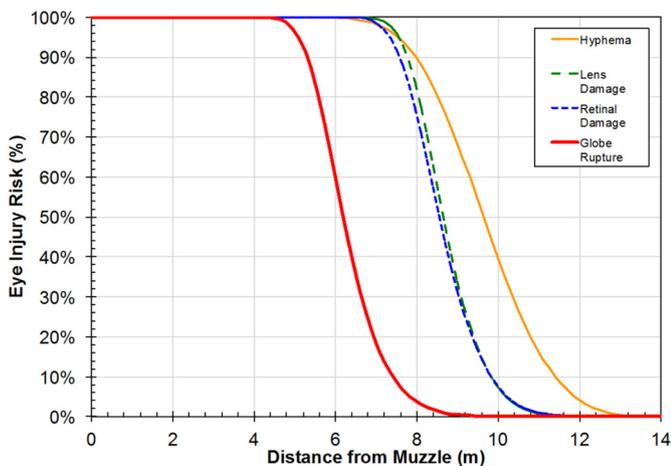


Fig. 4. Risk of various eye injuries by Dumas-Kennedy model as function of distance.

This is well illustrated by a published case report of a penetrating dart injury apparently without significant shoulder impact [18]. The dart entered the temporal limbus, traversed the inferotemporal iris and lens, and exited the inferior pars plana. A vitreous hemorrhage was present. Nylon sutures were used to close the corneal and scleral defects. The patient regained best-corrected visual acuity of 6/18.

It must also be stressed an eyelid appears to offer significant protection to the damage from the collar impact. A published case report describes a patient in which the probe landed with the eyelids closed [19]. The dart penetrated just above the infraorbital bony margin. There was a small subconjunctival inferior hemorrhage, but the cornea was intact. After dart removal, the wound was closed with vicryl sutures. The patient ended up with a pinhole visual acuity of 6/9.

4. Discussion

We believe that this paper represents the first biomechanical analysis of the risk of penetrating eye injury from electrical weapon probes. We applied a validated biomechanical eye injury model which shows that we can expect (1) hyphema, (2) lens damage, (3) retinal damage, and (4) globe rupture with existing probes at decreasing deployment distances for a centered impact.

These findings appear to comport with published data finding 12 enucleations and 6 cases of complete blindness and thus the majority (18/28) of probe impacts resulted in a loss of vision [7]. In total there have been 7 cases of partial blindness, and 2 cases of normal vision after successful surgical repair. (There was a case lost to follow-up after a surgical repair attempt.) See Table 1 for details. With 18 identified cases, there is a risk of 0.64, CI [0.47–0.82] for unilateral blindness or enucleation from a penetrating eye injury, primarily from globe rupture. See Fig. 5.

Globe rupture was usually associated with blindness or enucleation. However, there were 4 cases of unilateral blindness where the records were insufficient for us to determine if there was a globe rupture. Dart penetration (without significant impact energy from the probe

Table 1 Penetrating globe injury field use cases.

Year	Age	Sex	State	Code	Source
2004	50	M	AU	N	Ng & Chehade [19]
2005	21	M	CA	P	Kroll et al. [7]
2005	21	M	OR	P	Chen et al. [18]
2007	27	M	TX	B	Kroll et al. [7]
2007	18	M	CA	P	Kroll et al. [7]
2008	24	M	CA	B	Kroll et al. [7]
2008	25	M	CN	N	Han et al. [35]
2008	46	M	KR	E	Park et al. [36]
2009	43	M	TN	E	Kroll et al. [7]
2009	26	M	MO	E	Teymoorian [37]
2011	52	M	PA	E	Kroll et al. [7]
2011	19	M	TX	B	Kroll et al. [7]
2011	34	M	NM	P	Kroll et al. [7]
2011	27	M	FL	P	Kroll et al. [7]
2012	47	F	TX	UNK	Li and Hamill [38]
2013	24	M	OH	P	Kroll et al. [7]
2013	22	M	FL	B	Kroll et al. [7]
2014	36	F	QU	E	Kroll et al. [7]
2014	55	M	SctI	E	Kroll et al. [7]
2014	31	M	CA	E	Kroll et al. [7]
2014	21	M	WA	B	Kroll et al. [7]
2014	24	M	NY	E	Rafailov et al. [39]
2014	36	M	TX	E	Cahill and Jardeleza [40]
2015	22	F	MO	P	Kroll et al. [7]
2015	26	M	AL	E	Kroll et al. [7]
2015	20	M	QU	B	Kroll et al. [7]
2015	53	M	FL	E	Kroll et al. [7]
2017	31	M	NY	E	Kroll et al. [7]

SctI = Scotland. QU = Queensland, Australia. P = partial blindness (pinhole or blurred vision), B = blindness, E = enucleation.

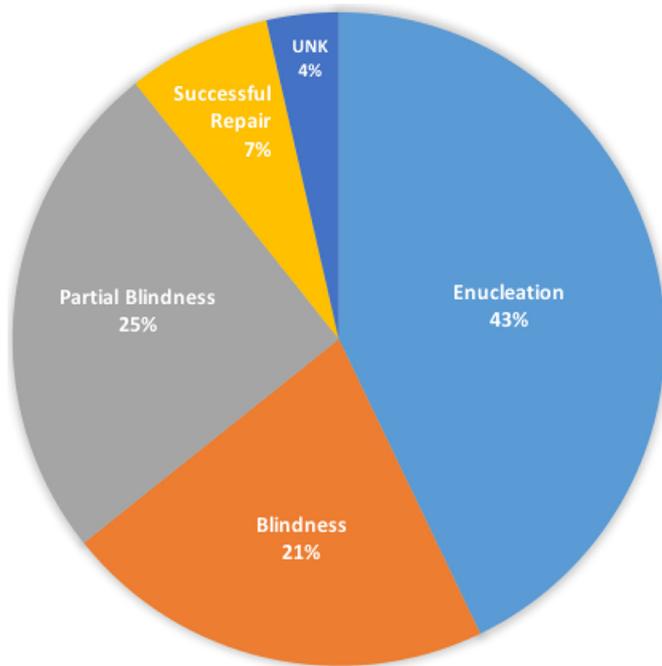


Fig. 5. Outcomes, including those unknown (UNK), after penetrating globe injury.

shoulder) was typically only associated with pinhole defects or minor blurring.

Electroporation is another possible means of tissue injury from the voltage spikes of CEWs. This has been well studied and the effects are limited to <1 mm from the probes where it helps sterilize the probes [20,21]. We suspect that there may have been some confusion caused by the media myth that CEWs deliver 50,000 V to the body vs. the actual 600 V [22].

We remain open-minded but somewhat skeptical of the occasional hypothesis of non-penetrating electrical eye injuries from electrical weapons for 2 reasons. (1) The electrical output (<2 W) appears too low to cause such damage by thermal effects, and (2) cases such as that of Jey, where there was a peri-ocular probe yet no reduction in vision [23].

The Axon-competitor models of probe-capable CEWs, PhaZZer™ Enforcer and the Condor™ Spark use essentially identical probes, and thus a similar eye injury profile is expected.

Within the limits of the published experience, the biomechanical model predictions appear to be consistent with field results.

There is a case of possible mechanical injury from the probe impacting *near* the eye. An Ontario, Canada provincial police officer was responding to a call about an out-of-control man at a home where he deployed his CEW and a probe lodged near the man's left eyelid. The man was taken to a local nursing station, treated, and released, but returned the next day with pain and swelling to his eye, and later underwent surgery for a detached retina.

We found another eyelid landing case that did not, however, produce ocular injury. A 36-year-old man was wanted for burglary, auto theft, and parole violations in New York. Deputies found him hiding in a field. When they approached him, the man pulled a knife. A deputy deployed his CEW and a probe struck the man in the upper left eyelid. The man apparently suffered no long-term injury or loss of vision.

Jey reported on a California subject struck in the left orbit [23]. CT findings revealed left preseptal hematoma, a small amount of hematoma under the left eyelid, mild proptosis, and no discernable evidence of orbital fracture, optic nerve, or ocular findings. Emergent evaluation under anesthesia noted an injury of the eyelid, with disruption of the globe in the posterior location with partial extrusion of blood and vitreous. He was treated for vitreous hemorrhage and a retinal tear, which

necessitated retinal photocoagulation. On the patient's last visit, he had 20/20 vision in his eye.

Sayegh reported a Maryland subject with a probe embedded in his right lower eyelid [24]. The probe created a subretinal hemorrhage that progressed into an exudative retinal detachment over 3 days. The retinal detachment gradually resolved, and visual acuity improved over the next 2 months. The report suggested that the injuries were electrical in nature. However, the authors supported that hypothesis with citations to lightning injuries and appeared to be unaware of the low 2-watt output of CEWs. It is possible that there was some electroporation damage [25,26].

In our search, we found another example of alleged electrical (non-ballistic) injury. Officers, in Florida, were attempting to subdue a burglary suspect. The suspect managed to turn the CEW toward a female officer's face just before it deployed. A probe hit her in the right temple; the other hit her near the bridge of her nose, just below her right eyebrow. According to media reports, it formed a direct current through her right eye, which allegedly left her blinded. We consider this possibility unlikely, given the significant difference in power between the CEW and RF cauterization devices. The low (<2 W) output of TASER CEWs can be compared to the typical 50–100 W required for electrocautery.

A final example of alleged electrical-ocular injury was the case reported by Seth [27]. A 35-year-old male presented, in Connecticut, with traumatic iritis, angle-recession glaucoma, and retinal dialysis secondary to "blunt" trauma from a CEW probe in his right eye 6 days previous. He was said to have an "electrical" cataract in the left eye, and minor skin burns on the left eyelid. The ophthalmologist successfully repaired the right eye, but the patient was lost to follow-up before he could attempt to repair the left eye. Cataract formation may occur in up to 5% of electrical injuries [28]. However, this usually involves massive energies, significantly greater than CEWs deliver, high enough to cause loss of consciousness and massive tissue necrosis [29,30]. For example, electrically-induced cataracts have been associated with extremity amputations [31]. Electrically-induced cataracts typically take months to develop but may occur within hours in cases of severe burns close to the eye [29,30].

There is no obvious lesson for the user of an electrical weapon. Often, a law-enforcement officer does not have control over the range for a frontal confrontation. Even if the range was the officer's choice there is no clear optimal range. A range of 6–9 m significantly decreases the risk of globe rupture in the event of a globe penetration. However, at, say, 7 m the aiming accuracy is proportionately reduced. With the probe dispersion angle of 8° the probe spread is 1 m so it is difficult to place the bottom probe in a leg while not having the top probe contact the face.

5. Guidelines for law enforcement and paramedics

When first responders confirm an embedded CEW probe in the periocular or ocular tissues they should follow general principles for emergency management of embedded foreign bodies. Namely, the probe should be left in place — as is — without attempting to remove or alter its position in any way as this could produce more harm to the visual structures.

Snip away any wire still attached to the probe. Any safe means of protecting the probe from changes in position may be attempted such as affixing a truncated paper cup over the area to act as a shield. Do not attempt to secure the probe to the patient's face or eyelid as eye movements may then cause a probe position change and further injury. The patient should be transported to an emergency department immediately where ophthalmologists should be consulted.

6. Treatment of probe-induced eye injury

We offer the guidance below for treating a CEW probe penetrating injury. This is based on our (RS & NKS) specific experience [32]. It is

also based on the present gold standard management of ruptured globes after injury [33,34].

In the event of a probe injury to the eye, it is imperative (1) to have only ophthalmological surgeons remove the probe, and (2) that care be taken to rule out a ruptured globe. Patients with anterior globe rupture often present with obvious distortion of normal ophthalmic anatomy; typically, these injuries are corneal or scleral lacerations which are associated with extrusion of intraocular contents. It is common to see iris prolapse from corneal wounds or uveal prolapse from scleral wounds. In the latter scenario, uvea, a dark material, which is often attached to vitreous (a clear gel) can be seen emanating from a scleral laceration. Anterior globe rupture can often be identified using a penlight.

In some cases, anterior globe rupture is less obvious, and examination with a slit lamp is necessary. In order to evaluate a conspicuous anterior globe rupture, an ophthalmologist should be expeditiously consulted to perform a Seidel test. In this examination, the surface of the eye is anesthetized with topical tetracaine or proparacaine drops, and a fluorescein strip is gently brushed across the site of suspected injury. In the case of a globe rupture, fluorescein-stained material will emanate from the injury in the form of a leak. Posterior globe rupture (much less likely) is more difficult to evaluate as it may not be obvious on initial exam. In some cases, the eye may appear shrunken due to loss of vitreous from an unidentified site. If the eye appears normal on anterior exam but posterior rupture is suspected, imaging should be performed. CT scan of the brain and orbits without contrast (preferably 1 mm slices) is the most efficient and safe imaging study. MRI is contraindicated in the presence of metallic foreign bodies. Alternatively, gentle ultrasound can be used to identify intraocular foreign bodies or posterior globe rupture. Ultrasonography should **not** be performed in the setting of concurrent anterior globe rupture.

Once globe rupture is determined, further examination of the globe should be deferred until surgical repair. No pressure should be placed on the globe and the eye should be protected with a shield. *A patch should not be placed over the eye.*

CEW probes have a 5% rate of *Staphylococcus aureus* contamination [21]. Systemic antibiotics with broad coverage such as Vancomycin and Cefazolin or Ciprofloxacin or 4th generation quinolones (moxifloxacin or gatifloxacin for better intraocular penetration) should be administered. Children with ruptured globes can be given Cefazolin and Gentamycin.

Endophthalmitis, ocular inflammation often in the setting of infection, is more likely in cases with dirty injuries, retained intraocular foreign bodies, rupture of the lens capsule, or long delays until surgical repair. Pain management and anti-emetic medications should also be administered as needed.

Surgical repair by a trained ophthalmologist should be arranged as soon as possible. Some practitioners recommend the use of intravitreal antibiotics during globe repair but this is not currently the standard of care. If the globe rupture is associated with skin lacerations near the eye, the laceration repair should be deferred in order to avoid accidental manual pressure on the globe during suturing. In cases where the globe does not appear to be salvageable by surgical intervention, enucleation of the globe should be considered. These surgeries should be performed within 7–14 days of the initial trauma to prevent the rare occurrence of sympathetic ophthalmia – an autoimmune inflammatory attack on the contralateral eye that can compromise vision of that globe.

7. Limitations

This work was based on a biomechanical model which was primarily validated with spherical and cylindrical projectiles. It is possible that the cylindrical CEW probe collar has a different eye injury profile when preceded by the sharp dart portion. A prospective experimental study could generate superior data compared to our modeling results. However, a relevant experiment would have difficulty obtaining ethical approvals.

Our modeling results appear to be consistent with published epidemiological data. However, those data are based largely on secondary sources.

8. Conclusions

A biomechanical model predicts that a globe rupture can be expected ($p = .5$) when the eye is within 6 m of the CEW cartridge muzzle and decreases with an increasing distance. Significant eye injury is expected from a penetration by an electrical weapon probe at close range. Not all penetrating globe injuries from electrical weapon probes will result in blindness.

Disclosures

MWK is a member of the corporate and scientific advisory boards of AXON (fka TASER) who partially funded this work. MAB is the principal of LAAW, LLC and a former employee of Axon. HEW is a retired police chief and received a speaking honorarium from Axon. MWK, MAB, and HEW have done expert witnessing in use-of-force cases. MBR, EAK, NKS, and RS report no conflicts.

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