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Systematic Review/Meta-analysis

Estimating the Risk of Cardiac Mortality After Exposure to Conducted Energy Weapons

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ABSTRACT

Background: Conducted energy weapons (CEWs), commonly known as Tasers, are a reputed nonlethal law enforcement weapon. Nevertheless high profile cases have suggested a causal association with cardiac death but the magnitude of any putative risk is unclear.

Methods: An electronic systematic review of all real world, cohort studies of consecutive CEW cases was performed. "Pessimistic" and "optimistic" previous beliefs about CEW mortality were derived from an unbounded internet search, including case series but excluding the previously identified cohort publications. A Bayesian analysis updated these previous beliefs with the published objective cohort data.

Results: Pessimistic and optimist previous beliefs with modes of 1/700 and 1/7000, respectively, and upper limits (< 2.5% probability) of 1/100 and 1/1000, respectively, were constructed. Three cohort studies formed the objective data source and their combined mortality was 1 in 2728 cases or 3.67/10,000 (95% confidence interval,

RÉSUMÉ

Introduction : Les armes à impulsions (AI), communément connues sous le nom de Taser, sont des armes réputées non mortelles par les forces de l'ordre. Néanmoins, des cas très médiatisés ont suggéré un lien de causalité entre le Taser et la mort cardiaque, mais l'ampleur de tout risque putatif n'est pas élucidée.

Méthodes : Une revue systématique électronique de toutes les études de cohortes réelles de cas consécutifs d'AI a été réalisée. Les croyances « pessimistes » et « optimistes » précédentes sur la mortalité liée à l'AI provenaient d'une immense recherche dans internet, y compris les séries de cas, mais à l'exclusion des publications de cohortes précédemment identifiées. Une analyse bayésienne a actualisé ces croyances précédentes par la publication de données de cohortes objectives.

Résultats : Les croyances pessimistes et optimistes précédentes par valeurs dominantes de 1/700 et de 1/7000, respectivement, et limites supérieures (probabilité < 2,5 %) de 1/100 et de 1/1000, respectivement,

Conducted energy weapons (CEWs) are one of several options along the use-of-force continuum used by law enforcement officials to facilitate arrests of uncooperative, violent individuals. These devices use electrical energy to inflict pain, immobilize, and ultimately incapacitate human subjects. Online video examples of CEW use associated with nonlethal and lethal outcomes have gone "viral."[1,2] Despite their purported design as nonlethal weapons, considerable debate is ongoing not only in the popular press/media but also in the medical literature[3-6] concerning the potential danger of CEWs to precipitate sudden cardiac arrest/death.

In 2008, Amnesty International summarized many in-custody deaths that were proximate to CEW exposure.[7] Recently, 8 cases of sudden cardiac arrest/cardiac death after CEW exposure have been reported in a high-impact cardiovascular subspecialty journal,[3] although any link to causality has been vigorously contested.[8] Based on these data and animal studies, it has been opined that CEW stimulation can cause cardiac electrical capture and provoke cardiac arrest resulting from malignant ventricular arrhythmias.[3] This interpretation of these recent and past cases has been called into dispute by noting underlying health issues in some of the victims and the lack of evidence for induced arrhythmias in numerous volunteer and epidemiologic studies.[4-6] In response to this debate, there has been a call "to transform the argument" from if CEW-induced mortality can occur to how often it occurs.[9] The goal of this report was to quantify the CEW mortality risk, as best possible, using probability models and to explicitly acknowledge the effect of previous beliefs in light of the paucity of quality objective data.

Methods

An electronic systematic review of all clinical studies was executed using the PUBMED, EMBASE, and Cochrane databases. The PUBMED query string used was: (((conducted OR conductive) AND (energy OR electric* OR electronic) AND (weapon* OR device*)) OR ((electric* OR electronic) AND (control OR discharge) AND (weapon* OR device*)) OR "stun gun" OR taser* OR "Conducted Energy Weapon

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1/107,751 - 1/490). The maximum a posteriori estimated risks of CEW mortality for the pessimistic and optimistic prior distributions were 5.3 and 2.2 deaths per 10,000 exposures, respectively. The upper limits (< 1% probability of occurrence) of the posterior distribution were 1 death per 408 and 982 CEW exposures for the pessimistic and optimistic previous beliefs, respectively.

Conclusions: Limited available evidence can be used to construct approximate boundaries for CEW mortality risk and suggests that the population risk of CEW mortality is likely small but not negligible. More high quality data are required to refine these estimates and extreme caution must be exercised before applying these population risks to individual cases.

ont été élaborées. Trois études de cohortes formaient la source objective de données et leur mortalité combinée était de 1 sur 2728 cas ou 3,67/10 000 (intervalle de confiance à 95 %, 1/107 751 - 1/490). Les risques estimés a posteriori maximaux de la mortalité liée à l'AI des distributions pessimistes et optimistes précédentes étaient de 5,3 et de 2,2 morts par 10 000 expositions, respectivement. Les limites supérieures (probabilité de survenue < 1 %) de la distribution postérieure étaient respectivement de 1 mort par 408 et de 982 expositions à l'AI pour les croyances pessimistes et optimistes précédentes.

Conclusions : Les rares données probantes disponibles peuvent être utilisées pour établir les limites approximatives du risque de mortalité liée à l'AI et montrent que le risque de mortalité liée à l'AI de la population est possiblement faible, mais non négligeable. Plus de données de haute qualité sont nécessaires pour affiner ces estimations. Il faut également faire preuve d'une grande prudence avant d'appliquer ces risques pour la population à des cas individuels.

Injuries"[Mesh]) AND ("Law Enforcement"[Mesh] OR "Police"[Mesh]) AND ("Retrospective Studies"[Mesh] OR "Prospective Studies"[Mesh] OR "Review"[pt] OR "Meta-Analysis"[pt]). Because consecutive real world (not volunteer) cohort studies represented the highest quality real world safety evidence available (no randomized trials having been conducted), only such studies in adults that also measured mortality were retained and formed the objective database. Specifically, animal, volunteer, modelling, case series, pediatric, and duplicate studies were excluded. Data were abstracted and validated by both authors. Only mortalities and total number of exposed individuals in the retained articles were abstracted. Mortalities in these studies were represented by binomial distributions, which are parameterized by the number of successes (deaths) in a sequence of independent yes/no experiments.

Direct probability statements can only be made if the objective data are conditioned on previous beliefs. This is the correlate of clinical decision-making in which test results are only sensibly interpreted in a clinical context. To determine the final (posterior) probability that CEWs are associated with mortality these objective data (likelihood) must be combined with previous beliefs about CEWs according to the following equation:

$$\text{Posterior distribution} = \frac{\text{Likelihood of data} \times \text{previous distribution}}{\text{Normalizing constant}}$$

Although Bayes' Theorem as expressed in the preceding formula follows the formal rules of probability in an uncontested and irrefutable mathematical manner, the difficulty becomes in choosing a previous distribution. One approach to this difficulty is to accept that no single previous belief will reflect everyone's beliefs. Therefore "pessimistic" (belief in high CEW mortality risk) and "optimistic" (belief in low CEW mortality risk) previous beliefs for putative CEW mortality might be established.[10] For example, a "pessimist" might believe the risk of CEW-related mortality is far from rare because of the many incidents reported in the media and the "optimist" might believe that the safety information supplied by the manufacturer concerning volunteer and animal studies is reassuring. Medical electronic and unbounded internet searches were also performed to find all reports, excluding the objective cohort studies already mentioned for the likelihood of CEW-associated mortality and this was used to derive transparent explicit previous probabilities for CEW mortality.

Although a large range of potential previous beliefs is to be expected initially, as more objective data accumulate, the effect of the previous beliefs will reduce and the posterior beliefs (distributions) of the "optimist and "pessimist" will converge. These previous distributions can be fully characterized by specifying 2 parameters; the mode and a measure of the spread or variation, typically an estimate of an upper limit delineating the point at which there is a less than 2.5% probability that the result would fall. For the mathematical convenience of simple closed-form calculations for the posterior distribution, we used Beta prior distributions, the conjugate family for the binomial likelihood. A Bayesian analysis is thus essentially an updating of the "pessimistic" and "optimistic" previous beliefs with the best objective data available.

To determine the effect of future studies on the estimate of CEW mortality and to assess how quickly our subjective previous estimates become dominated by newly observed high-quality prospective data, we performed an additional analysis that assumed that a new cohort with 4 times the currently available data were to become available.

Computations were done using the R software.[11]

Results

The objective data

The literature search identified 41 studies via PubMed, 105 from EMBASE, and none in the Cochrane library. From this sample only 3 large high-quality independent multicentre cohort studies that recruited consecutive patients were retained. The first study reported no CEW-attributed deaths in 1201 consecutive cases of CEW deployment.[12] There were in fact 2 fatalities that were judged by medical examiners not to be causally related to the CEW. However, 1 fatality occurred within 5 minutes of CEW deployment and we will

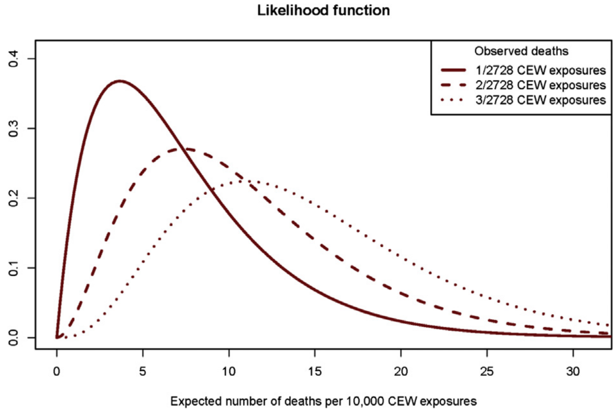

Figure 1. Likelihood function expressed on the scale of deaths per 10,000 conducted energy weapon (CEW) exposures based on 3 cohort studies of consecutive individuals.[12-14]

assume, contrary to the study event adjudicator, that the CEW was causally responsible for the death. Another cohort study,[13] conducted from 2001 to 2006, also reported no deaths in 1101 consecutive CEW uses. A third study[14] reported 426 consecutive CEW deployments from November 2004 to January 2006, and a single death that occurred 12 hours after CEW deployment, which again was deemed not to have been caused by the CEW, but by other factors (hyperthermia, severe cocaine intoxication). Based on these 3 cohort studies combined, the estimated risk of CEW death is therefore 1/2728 or 3.67/10,000. A 95% confidence interval, computed using an 'exact' binomial method, ranged from 0.093 to 20.4 per 10,000, indicating that based on these data alone one cannot exclude the possibility that the risk of death might be as low as 1 in 107,751, or as high as 1 in 490. If both deaths in the first cohort study[12] were attributed to CEWs then the risk could be as high as 26 per 10,000, and if the death from the third study was also assumed to be caused by CEWs then the risk could be as high as 32 per 10,000 (see Fig. 1). Conversely, if the original adjudication of no deaths causally related to CEWs is accepted then the mortality risk estimated from these cohort studies is likely $<$ 14 per 10,000.

Previous beliefs

As mentioned previously, these objective data can only be sensibly interpreted in the context of previous beliefs about the safety of CEWs. There is no single definitive previous belief and these might range from a "pessimistic" to an "optimistic" view. The "pessimist" might believe the risk of CEW-related mortality is far from rare because many incidents have been reported in the media. For example, Amnesty International[7] reported 334 deaths after CEW use in the United States from June 2001 to August 31, 2008. Another Internet site (http://electronicvillage.blogspot.ca/2009/05/taser-related-deaths-in-united-states.html) claims that in the United States 351 people died in the period 2000-2008 and 186 in the period 2009-2012 after CEW exposure. Specific yearly death rates are not provided in either case. Although it is perhaps highly unlikely that all of these in-custody deaths were causally related to CEWs, for the "pessimistic" viewpoint we will nevertheless assume that all of the approximate 100 in-custody deaths reported in the 2005-2008 timeframe were indeed caused by CEWs. Unfortunately, the exact number of annual CEW deployments is unknown. The worldwide estimate of CEW deployments that occurred during the period 2005-2008 is approximately 300,000[15] but no information is provided about how this number was derived. Therefore, we have conservatively estimated the number of deployments in the United States using indirect evidence. In a US population-based publication on use of force injuries, it was reported that in 2005-2008 approximately 35,000 emergency room (ER) visits occurred because of nonfatal CEW injuries.[16] Although the percentage of CEW exposures that led to these hospital visits is unknown, it was reported to be 17% in one large cohort study.[12] If, instead of this 17% ER visit event rate that one assumes, again pessimistically, that 1 of every 2 CEW exposures (50%) would cause a nonfatal injury leading to an ER visit, the most likely pessimistic previous mortality risk belief becomes 100 deaths per 70,000 exposures or 1 death per 700. To fully describe the "pessimist" previous distribution, we require some measure of its spread. The pessimist might argue that because of unreported events the risk might be much higher, perhaps even as high as 1/100. We have assumed that most "pessimists" would accept that there is only a small probability (2.5%) that the mortality risk is $>$ 1 per 100 CEW exposures. This upper boundary seems empirically justified because it represents a signal to noise ratio (the inverse of the coefficient of variation) $<$ 0.3. Moreover, this choice of spread for the previous distribution seems intuitively justified when it is recalled that previous information can also be expressed as an "effective number" of previously observed events. In this case, the parameter choices correspond to 0.72 deaths in 505 exposures (corresponding to a β [1.72-505] prior). Because of the limited amount of objective data, a much stronger previous belief would be difficult to justify for most reasonable people.

For the "enthusiast" or "optimist" previous belief we apply the same logic. The "optimist" might believe that because of claims of theoretically safe waveforms, to negative animal, volunteer, and computer simulation studies, and to the manufacturer's claims of absence of definitive proof regarding the CEW's ability to induce ventricular fibrillation in humans that the previous risk of CEW-induced mortality is very low.[15,17] Apparently, the manufacturer, who would surely be judged an "optimist," has quoted mortality rates in the vicinity of 1 in 100,000[9] and, although it is impossible to accord an exact "optimistic" probability, this is likely much lower than most reasonable people would be comfortable with. A more cautious "optimistic" opinion of the previous mortality risk might be in the order of 1 in 7000 or 1/10 the risk of the "pessimist's" previous belief. The "optimist" might also believe that the upper limit of risk ($<$ 2.5% probability) is $\leq$ 1/1000. As previously mentioned, an equivalent way to think about this previous belief is to think in terms of the number of events as a representation of the quantity of information contained in the prior belief. This assumption about the "optimist's" previous belief translates to 0.72 deaths in 5050 exposures (corresponding to a β [1.72-5050] prior). Notice that the "pessimist" and "optimist" previous beliefs are quite vague, as reflected in the low number of "effective" cases they contribute. In this case, this appears appropriate because the objective data are also

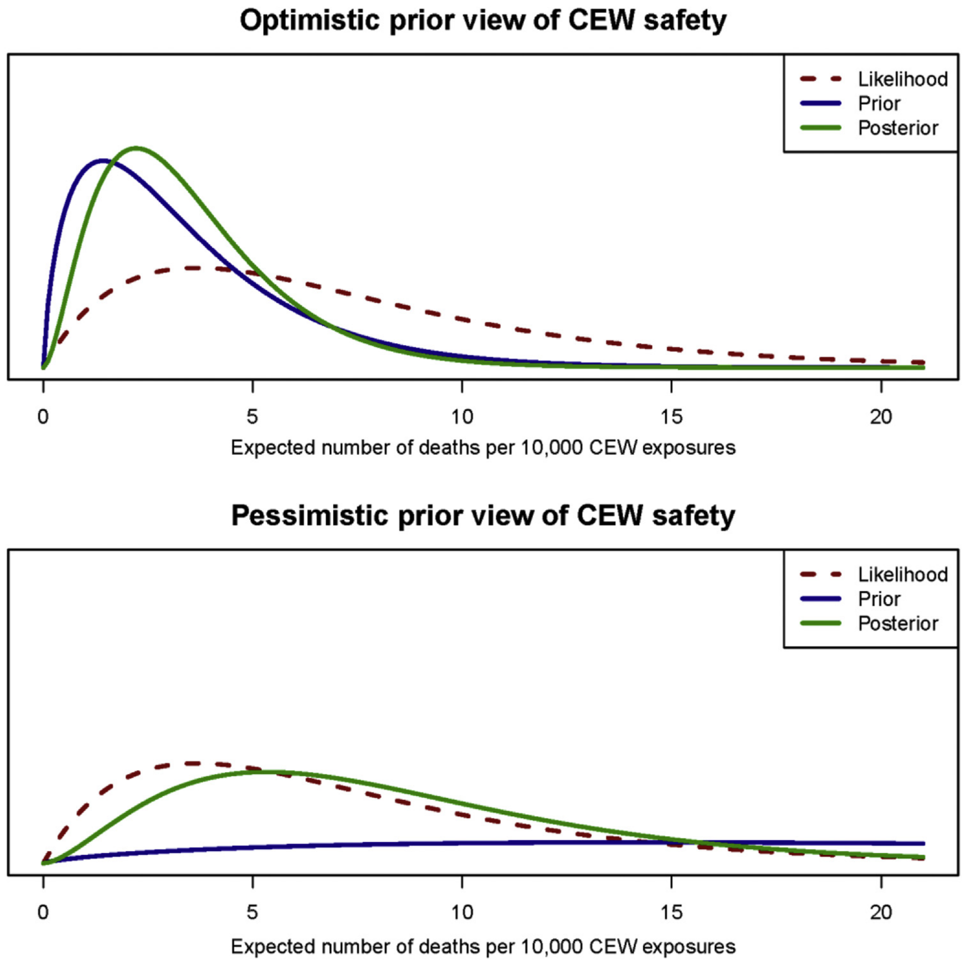

Figure 2. Prior and posterior distributions of the risk of death from conducted energy weapons (CEWs) expressed on the scale of deaths per 10,000 CEW exposures for 2 prior beliefs (optimistic and pessimistic) of CEW-associated mortality.

sparse and would otherwise be totally dominated by the perhaps not unreasonable, but nevertheless subjective, previous beliefs.

Posterior beliefs

For the "enthusiast" or "optimist", using Bayes' Theorem, the best estimate of the posterior probability of CEW-associated mortality after updating their previous belief with available objective evidence from the published literature is 2.2/10,000 with minimal chance (< 1% probability), that this would exceed 1 death per 982 exposures. In contrast, the "skeptic" or "pessimist" should believe, after updating his previous beliefs with the best available objective data,[11-13] that the most likely CEW mortality risk is 5.3 deaths per 10,000 exposures with a very small probability (< 1%) that this would exceed 1 death per 408 exposures. These distributions are displayed in Figure 2.

Because the estimates of CEW mortality vary depending on somewhat subjective previous beliefs, further research is needed. It would be interesting to investigate the effect of a large multicentre prospective cohort study on these posterior estimates. Suppose a new registry or previously unpublished study was identified with 4 immediate deaths likely causally related to CEWs in 10,000 exposures. Our previous posterior distributions in Figure 2 could now serve as our previous beliefs and the incorporation of these new data would result in the new posterior distributions shown in Figure 3. Figure 3 demonstrates that as more objective data accumulate the importance of the original subjective pessimistic and optimistic previous beliefs dissipate and the posterior distributions become similar. With this hypothetical data the pessimistic and optimistic modes have quite quickly equalized to approximately 4 deaths per 10,000 CEW exposures. This rapid equalization speaks to the vague nature and low power we assigned to both initial previous beliefs and their dominance by the accumulating evidence.

Of course, other outcomes for the hypothetical study might be considered; outcomes closer to the largest or smallest mortality estimate bounds. An outcome of 2 deaths in 10,000 exposures would shift both posterior much farther to the left (Fig. 4), and an outcome of 8 deaths in 10,000 exposures would shift both to the right (Fig. 5), again confirming the vague nature of the initial previous beliefs. Notice that again in both cases as more objective data accumulate the importance of the original pessimistic and

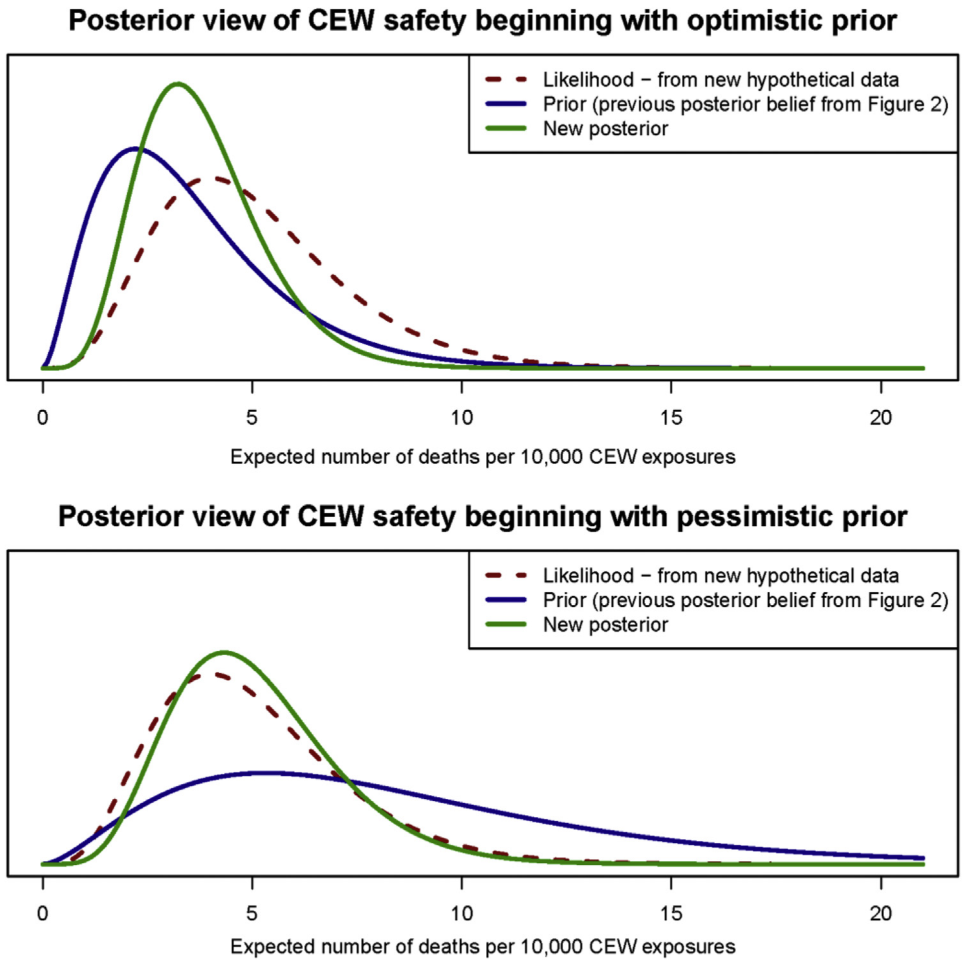

Figure 3. New (updated) posterior distributions of the risk of death from conducted energy weapons (CEWs) expressed on the scale of deaths per 10,000 CEW exposures after the accumulation of data from a new hypothetical study with an outcome of 4 deaths in 10,000 CEW exposures using the previous optimistic and pessimistic posterior distributions from Figure 2 as the new prior distributions. Notice that as more objective data accumulate the importance of the original pessimistic and optimistic previous beliefs dissipates and the posterior distributions become similar.

optimistic previous beliefs dissipate and the posterior distributions become similar.

Discussion

In this report, we have quantified the mortality risk after CEW exposure, as best possible, using explicit probability models and all available data sources and evidence. This analysis recognizes that the, at least partially subjective but not unreasonable, differing previous beliefs and especially the paucity of quality objective data will obviously leave some residual uncertainty in these estimates. Nevertheless, these results suggest that with a high degree of certainty the CEW mortality risk is < 1 death per 408 exposures (0.25%) and possibly < 1 death in 982 exposures (0.10%). This current analysis provides a more precise estimate of CEW mortality than a previous review article reporting a very wide mortality range from 0.0% to 1.4%.[18]

The present analysis takes no position on the appropriateness of CEW use as this would seem best decided by law enforcement agencies and their governing bodies. Rather, in this analysis we tried to present in a transparent and mathematically sound manner the risks of CEW mortality while acknowledging differing but reasonable previous beliefs. Although the results of this analysis suggest that the risk of CEW mortality is likely small it should not be concluded that it is inconsequential. Results of our analysis suggest that the risk is possibly several orders of magnitude larger than what has been suggested by the manufacturer.[9] In absolute terms, it has been estimated that between 100 and 300 people per million US adults are exposed annually to CEWs.[15] Although we appreciate a possibly large amplification of errors in extrapolation to a population level, our analyses, if correct, suggests that between 30 to 60 individuals (based on the "optimist" and "pessimistic" previous beliefs, respectively) might possibly die annually because of this "less than lethal" technology.

The present analysis does show how indirect and incomplete evidence can be used to provide approximate boundaries as to the risk of mortality after CEW exposure. Clearly, more high-quality data are required to refine these estimates and remains a desirable goal. As more objective data become available the probability distribution functions will narrow and the previous beliefs will become less important and the

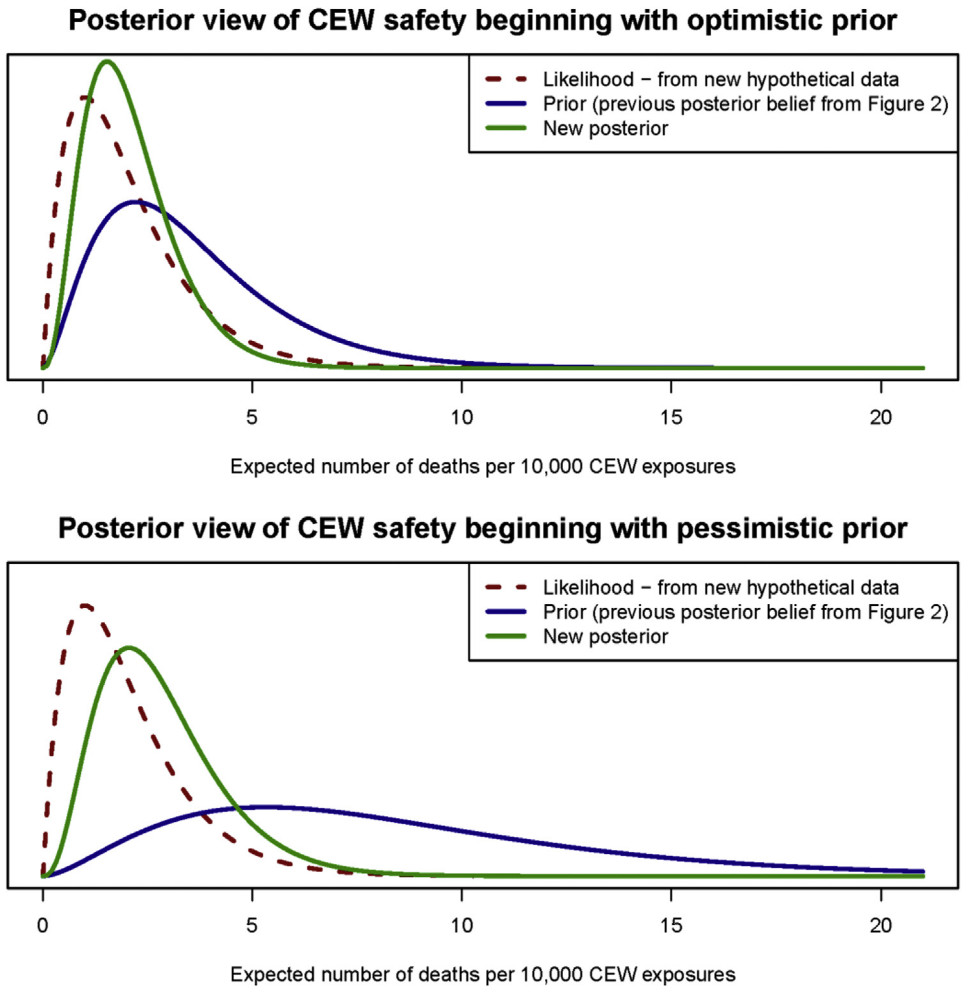

Figure 4. New (updated) posterior distributions of the risk of death from conducted energy weapons (CEWs) expressed on the scale of deaths per 10,000 CEW exposures after the accumulation of data from a new hypothetical study with an outcome of 2 deaths in 10,000 CEW exposures using the previous optimistic and pessimistic posterior distributions from Figure 2 as the new prior distributions. Notice that as more objective data accumulate the importance of the original pessimistic and optimistic previous beliefs dissipate and the posterior distributions become similar.

"optimist" and "pessimist" posterior opinions will converge. We demonstrate that this rapid convergence occurs with only 4 additional deaths from a hypothetical new study of 10,000 CEW exposures. Perhaps this demonstrated benefit of future studies might serve as an added impetus to collect more systematic high-quality data in a timely manner so as to improve our CEW mortality estimates.

A strength of the present study is its transparency in stating the range of previous beliefs. Current debate has been clouded by accusations on both sides of the debate concerning conflicts of interest and potential bias.[4-6,9] Our main limitation rests with the paucity and quality of the objective data. It should be noted that the literature does not permit an estimate of CEW mortality for each shock applied but rather for each CEW encounter, which might entail several shocks for some individuals. Also we have not considered other serious but nonfatal injuries. We have also made no estimate of possible injuries avoided by the avoidance of lethal weapons. Although CEWs are believed to reduce lethal weapon injuries to suspects and officer injuries, the evidence to support this seems fragile.[19] Further, no consideration has been given to the risk of other competing causes of death.

Finally, we have provided only an estimate of the overall marginal risk of CEW mortality. Extreme caution should be exercised in applying these population risks to individual cases because potential competing causes and mediators of mortality including location of the CEW darts with a likely higher risk for chest "hits," number of CEW deployments, underlying individual cardiac pathology, concomitant use of physical and chemical restraints, drug intoxications, and their potential interactions with CEWs need to be considered. This is not dissimilar to the judgement required in attempts to extrapolate the overall results from a clinical trial and apply them to individual patients.

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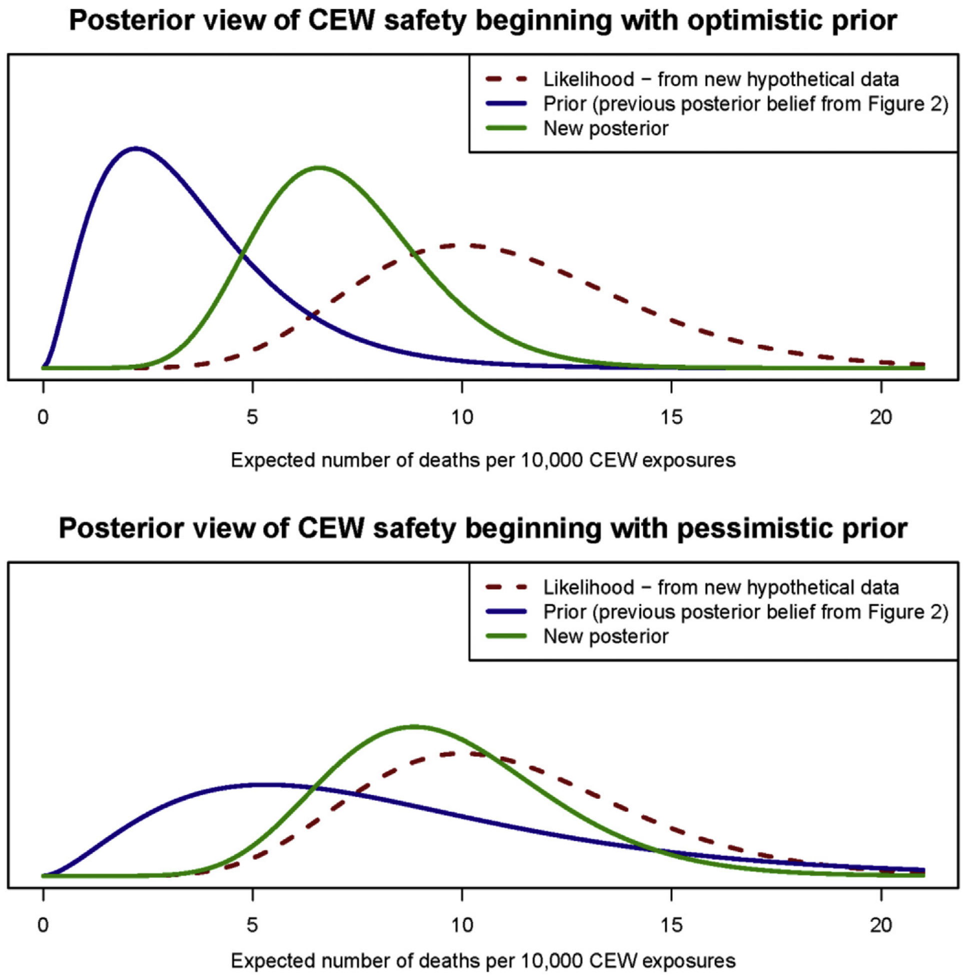

Figure 5. New (updated) posterior distributions of the risk of death from conducted energy weapons (CEWs) expressed on the scale of deaths per 10,000 CEW exposures after the accumulation of data from a new hypothetical study with an outcome of 8 deaths in 10,000 CEW exposures using the previous optimistic and pessimistic posterior distributions from Figure 2 as the new prior distributions. Notice that as more objective data accumulate the importance of the original pessimistic and optimistic previous beliefs dissipates and the posterior distributions become similar.

Disclosures

The authors have no conflicts of interest to disclose.

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