Analysis of the Quality and Safety of the Taser X26 devices tested for Radio-Canada / Canadian Broadcasting Corporation by National Technical Systems, Test Report 41196-08.SRC

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The purpose of this analysis is to review the tests carried out for Radio-Canada / Canadian Broadcasting Corporation by National Technical Systems (NTS) on 44 Taser X26 devices so as to answer the following two questions:

1. Do any of the tested X26 devices have abnormal electrical characteristics?
2. What are the possible safety implications of abnormal X26 devices?

1.1 Defining normal and abnormal electrical characteristics

The electrical characteristics of the X26 devices published by Taser International (Scottsdale, AZ, USA) are the following:

Table 1. X26 specifications for a 400 Ω load

peak voltage	1200 volt
peak current	3.3 ampere
average current	2.1 milliampere
energy per pulse	70 millijoule

and the range of normal values is ±15%[1]

In a realistic situation, the X26 device generates an electrical current between two barbs projected on the body surface. The electrical resistance (“the load”) between those two barbs can vary greatly because of factors such as the depth of penetration of the barbs in the skin, or even the absence of penetration in which case the current flows through an electrical spark between the barb and the body surface. Thus, it is important to test the devices over a wide range of electrical loads, here: 30, 100, 250 and 1000 Ω.

Since the electrical characteristics of the X26 depend on the load, the ±15% limits must be defined not only for the 400 Ω load, but for the entire range of load values. Figure 1 shows the average and individual values measured for each load of the four electrical characteristics of Table 1 *versus* the load connected to the fully extended wires of the X26.

[1] *“Peak arcing voltage measurement of TASER X26 and M26 devices”* by Max Nerheim, Vice President, Research and Development, Taser International, May 21, 2008.

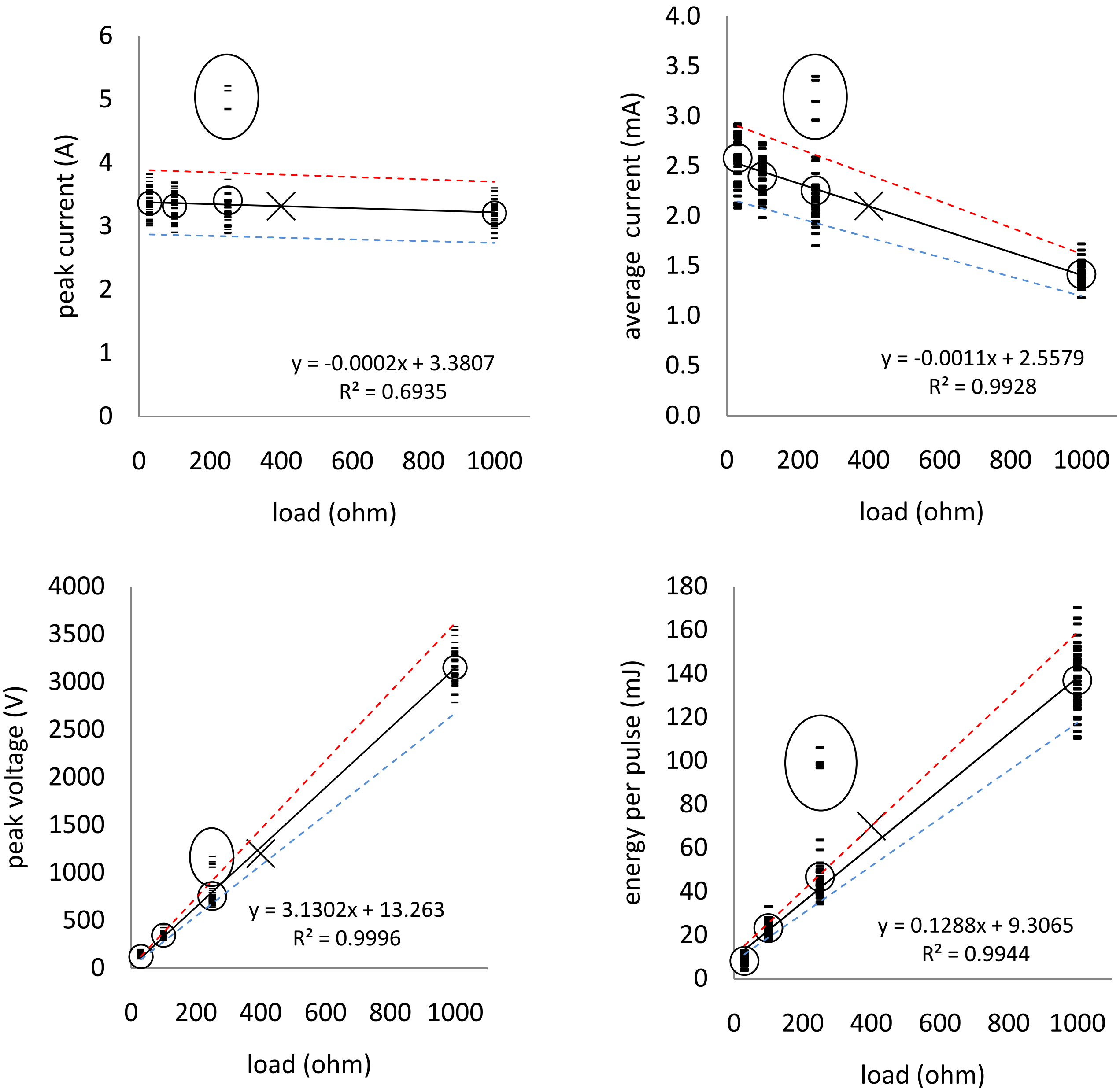


Figure 1. Electrical characteristics of the Taser X26 *versus* the load (ohm) connected to the fully extended wires (measured for the first pulse): dash symbols (-) indicate values for individual devices; large open circles (○) represent the average values for each load (*N*=41); black lines are regression lines for these average values and their equations are shown in the bottom of each figure with the squared value of the correlation coefficient R^2; the **✕** symbols represent the specification values given by Taser International for a 400 Ω load; the dotted red lines represent the +15% limit applied to the average value for a specific load; the dotted blue lines represent the -15% limit; NOTE: data points from four devices with abnormally high output are encircled, these abnormally high values were observed for the 250 Ω load because the first measurement on any device was always performed at 250 Ω.

First, these results show a very high degree of coherence and correlation with the average values obtained for each load (○) falling on the black linear regression lines.

Second, from an electrical engineering standpoint, the X26 tends to behave as an ideal current source instead of an ideal potential source because the peak current remains approximately same (3.3 A), whatever the value of the load. This is a desirable feature because the same current will produce the same electrophysiological effect whatever the resistance of the load. It follows that the peak voltage and energy per pulse are directly proportional to the load. The average current decreases with an increasing load value because of the internal impedance of the device.

Third, the values specified by Taser international at 400 Ω (Table 1) fall exactly on the black regression lines for the peak current and the average current, and they fall near the regression lines for the peak voltage and the energy per pulse. This confirms that the NTS sample is representative and that the NTS methodology is comparable with that of Taser International. However, the interpolated values are higher for the peak voltage (1242 V instead of the specified 1200 V, probably because 1200 V is a rounded number, although a 1300 V value is also found in the Taser literature), and lower for the energy per pulse (60 mJ instead of the specified 70 mJ, probably because more complex computations are involved as well as differences in the duration of the analysis window). Finally, the pulse rate for each device was determined once at 250 Ω using a low resolution recording that captured 6-8 sequential pulses.

1.2 Detecting the abnormal devices

The application of the extrapolated ±15% limits appears quite adequate for the peak current because all values (except 4) are within these limits. For the other characteristics, more values exceed these limits and these limits could be redefined. However, this is not necessary at this point because a visual analysis of Figure 1 clearly shows that some points have much higher values than expected, these points all correspond to the same four devices. The characteristics of these four devices are presented in the following Table:

Table 2 X26 taser devices with abnormal high output

Taser identification	Load (Ω)	Peak current (A)	Average current (mA)	Peak voltage (V)	Energy per pulse (mJ)
A03	250	5.212	3.40	1115	97.9
A09	250	4.857	3.15	1090	99.1
A18	250	5.138	3.36	1170	96.8
B03	250	4.840	2.96	1059	106.0

Thus, **EIGHT UNITS HAD GROSSLY ABNORMAL** electrical characteristics:

- **Three units could not generate any current,** even with charged battery packs (A06, A29, A30)

- **One unit could not generate current in a sustained manner when first loaded,** the H01 unit worked as expected during an open air spark test, but when connected to the load it only ran for a few cycles and stopped. Several consecutive tests on the same unit showed the same behaviour. After a dozen attempts, the unit worked properly and testing could then be completed.
- **Four units generated currents above the +15% limits** when connected to a 250 Ω load (A03, A09, A18, B03) as shown in Table 2.

The measurement of peak current and peak voltage values was semi-automated. The operator validated the peak values determined by the scope and sometimes rejected artifact due to electrical noise. The following Figure 2 confirms the validity of all the abnormal values shown in Table 2.

Figure 2A Taser A03 at 250 Ω.

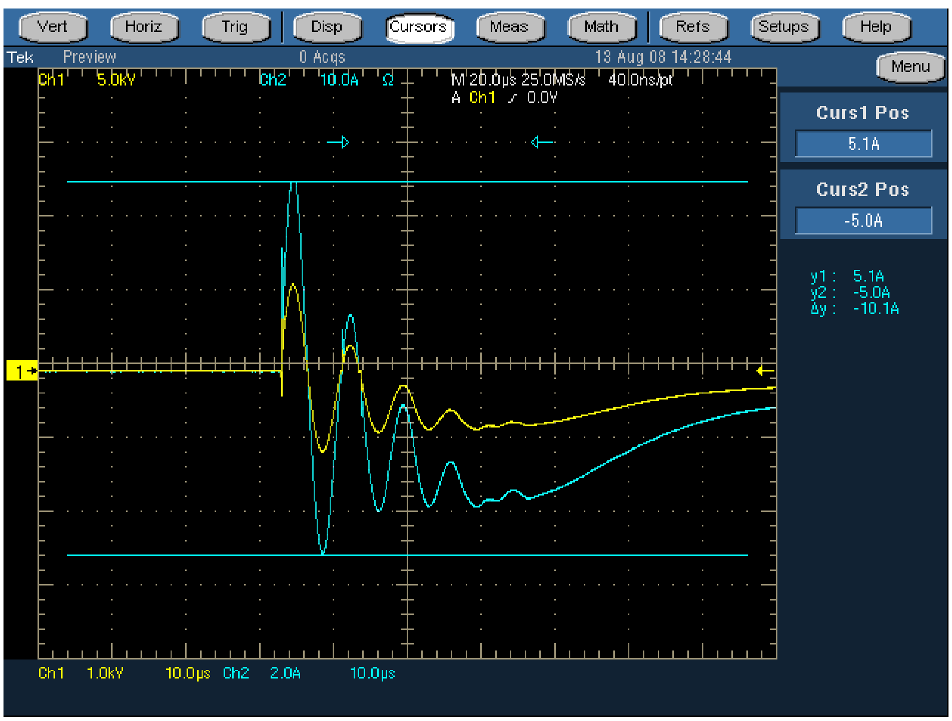


Figure 2B Taser A09 at 250 Ω.

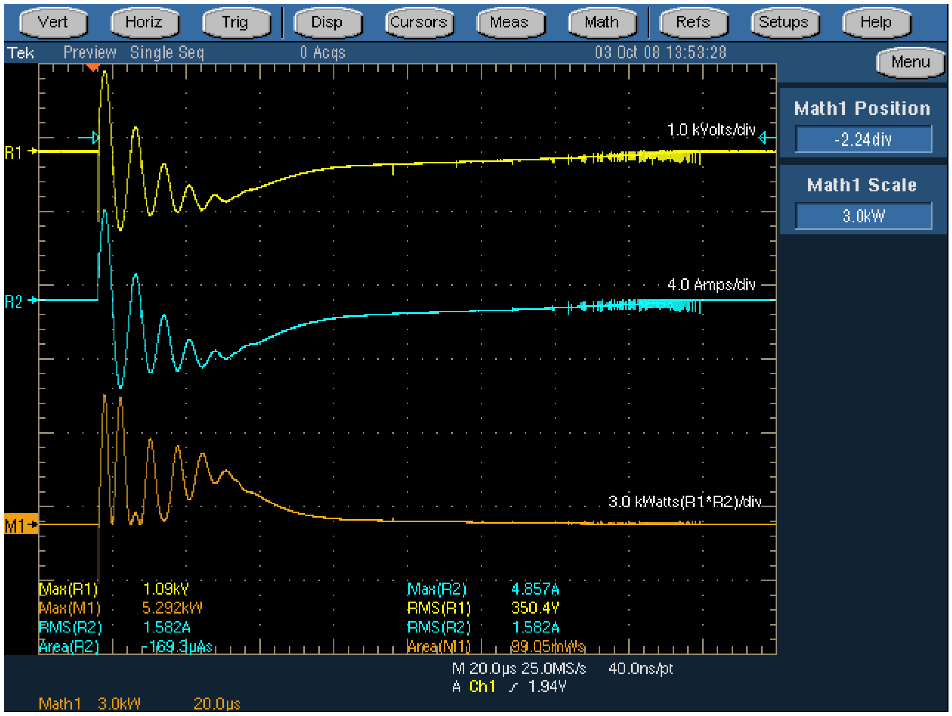


Figure 2C Taser A18 at 250 Ω.

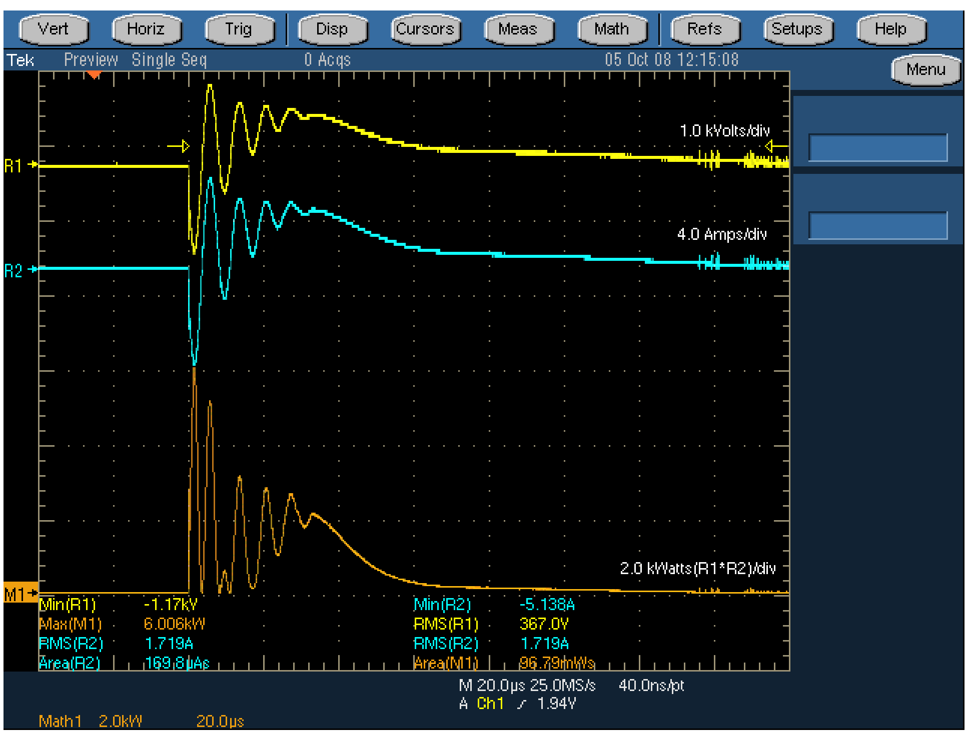
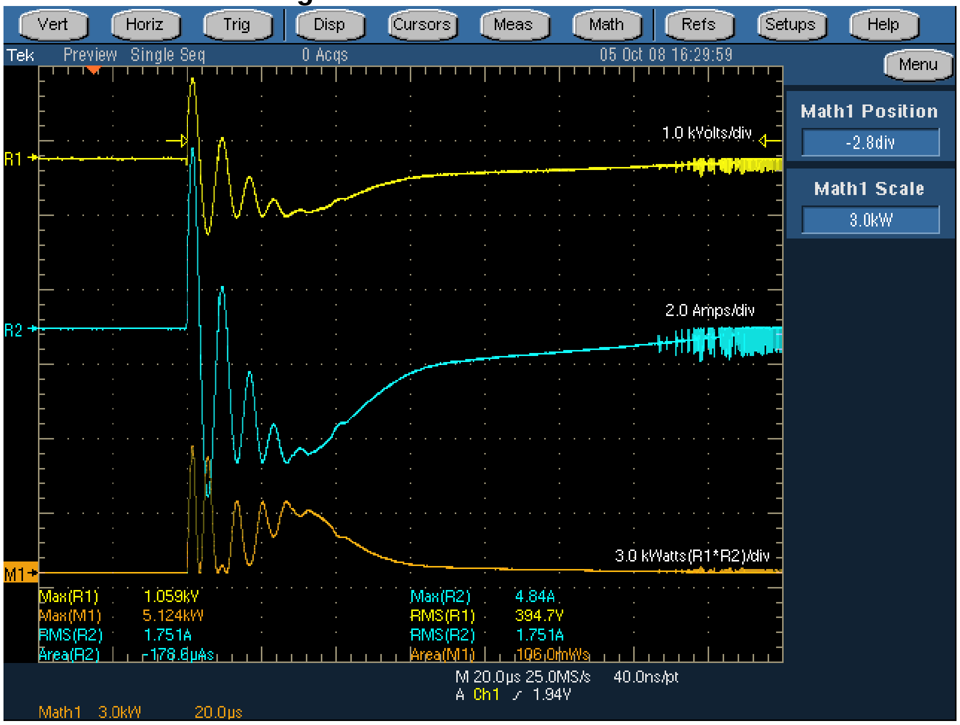


Figure 2D Taser B03 at 250 Ω.



1.3 Intermittent nature of the abnormally high current values

It is important to note that the NTS measurements were always performed using the 250 Ω load for the first test because that load is recommended by Taser International[2]. For the four X26 devices that showed abnormally high current, the first test always showed the highest current. Also, a delay could be observed between the pull of the trigger and the electrical discharge for these devices. Two of these units (A03 and A18) were tested a second time using the same resistance (250 Ω) and extended wires. **For both units, the second measurements showed lower, but still abnormal peak current: 3.98 A and 4.23 A respectively** (Figure 3). The four X26 devices that showed abnormally high current values at 250 Ω, subsequently showed normal values when connected to the other resistances (30, 100 or 1000 Ω).

Taser International recommends that a daily "spark test" should be conducted by police officers once every 24 hours or prior to the start of their shift. The purpose of this spark test is to verify that the Taser device is working properly and the battery is adequately charged, and because: "*There are components in the high voltage section of the X26 that are more reliable when energized ("conditioned") on a regular basis"* [3].

In most cases, this spark test was not performed prior to the NTS measurements. The NTS measurements otherwise suggest that "the lesser reliability of high voltage components when not energized on a regular basis" can produce delayed initial pulses with higher current values.

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[2] The Canadian Police Research Center. Testing of conducted energy weapons, July 2008

[3] TASER® X26E Operating Manual • MMU0004 Rev: B page 13

Figure 3A Taser A03 at 250 Ω: repeated measurement performed immediately after a 1.067 second burst (20 pulses) whose first pulse had a peak current of 5.1 A (Fig. 2A). The peak current is now 3.98 A.

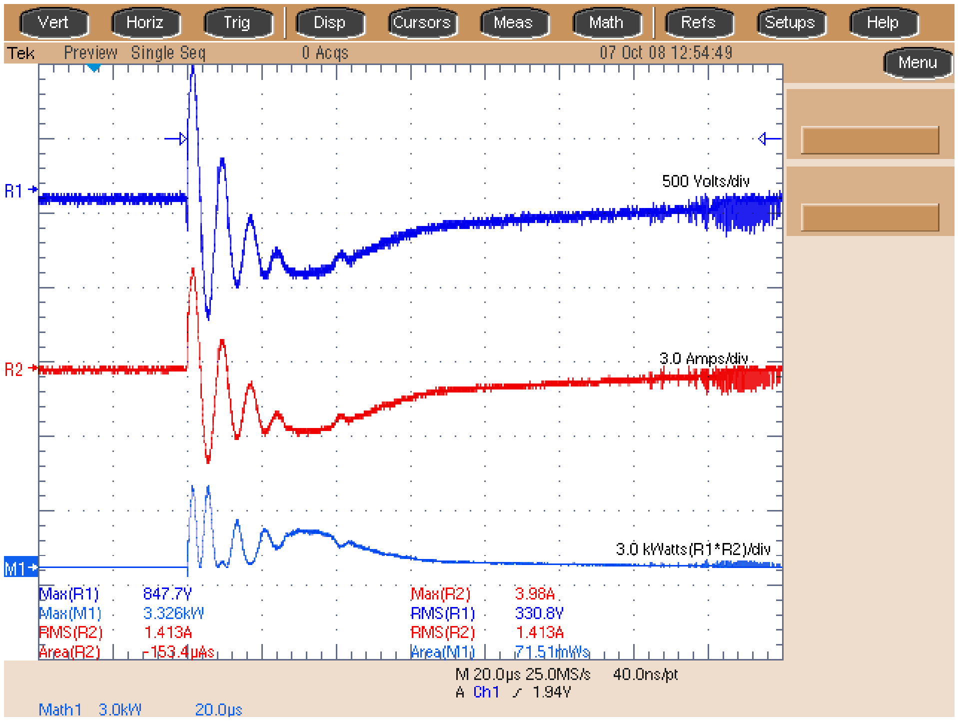
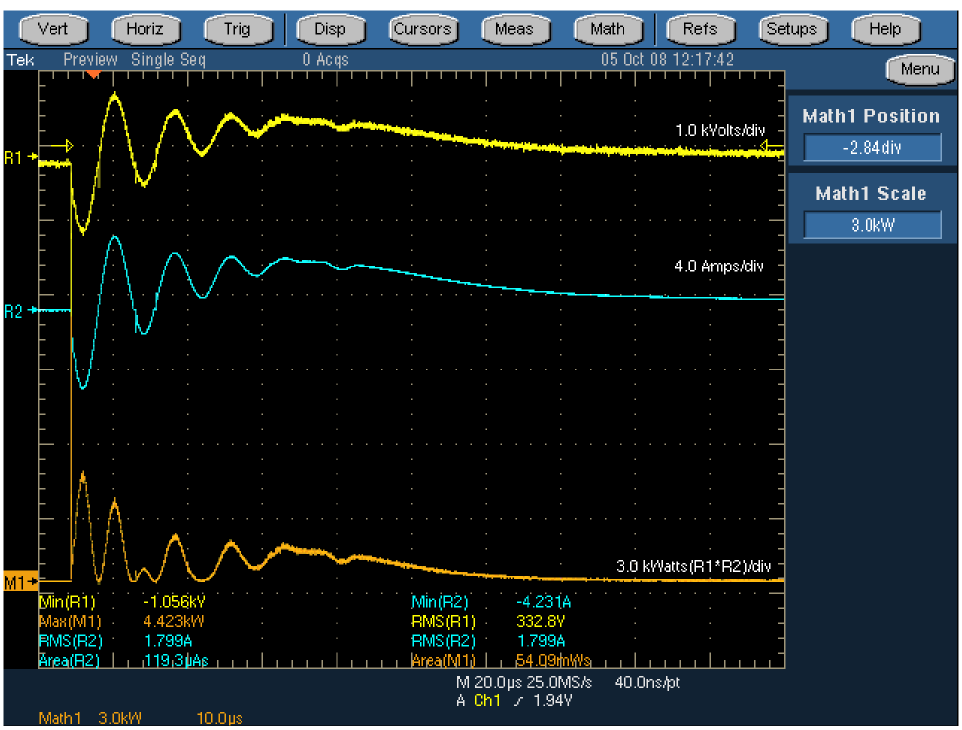


Figure 3B Taser A18 at 250 Ω: repeated measurement performed one day after a 2 second burst (39 pulses) whose first pulse had a peak current of 5.138 A (Figure 2C). The peak current is now 4.23 A.



These high voltage components "that are less reliable when not frequently energized" could be "spark gaps". A spark gap consists of an arrangement of two conducting electrodes separated by a gap usually filled with a gas. When the voltage reaches a certain threshold, a spark forms, ionizing the gas and drastically reducing its electrical resistance. Typically, a circuit would charge a high voltage capacitor and when its voltage reaches the spark gap threshold, current is rapidly drained through the spark gap. If the spark gap threshold is higher than normal, it takes more time to charge the capacitor (*hence the observed delay*) and the output current is greater. After sufficient current has flowed in the gas chamber of the spark gap, residual gas ions subsequently reduce the spark threshold for an indeterminate period of time.

Figure 3A shows that the first measured pulse in the A03 device was not sufficient to "energize" or "condition" the high voltage components and to reduce a peak current of 5.1 A (Figure 2A) to normal values. This measurement was repeated after about 20 pulses, but it still showed an abnormally high peak current value of 3.98 A that exceeded the +15% limit.

In practice, even if police officers are instructed to perform daily spark tests, it cannot be assumed that they will always perform them, especially since the X26 operating manual does not specify that a lack of spark tests may result in delayed firing or the possibility of elevated current output.

1.4 Age of devices with abnormally high current values

None of the devices were "spark tested" before the measurements and the majority of them showed normal current values.

Only four devices showed initial, transient, abnormally high current values (Table 2). Interestingly, these four devices were amongst a group of six devices that were bought before 2005. Thus, there is a very strong statistical association between older devices and higher current values[4].

Since 67% of the older devices (made before 2005) showed this type of problem, this raises concerns about quality control during manufacturing, possible change of design and component aging.

[4] Fisher's exact test, $p < 0.001$

2. Safety of abnormal devices

To evaluate the impact on the safety of abnormal X26 devices that generate peak currents that are 47% to 58% higher than the values specified by the manufacturer, the method described in the following publications of the International Electrotechnical Commission[5] to evaluate the risk of electrical current will be applied:

- IEC 60479-1 (third edition 1994). Effects of current on human beings and livestock. Part 1: General aspects;
- IEC 60479-2 (third edition 2007). Effects of current on human beings and livestock. Part 2: Special aspects.

The first step in the application of the guidelines is to identify which of the IEC standard waveforms is applicable. The NTS Report shows that the X26 device generates a series of very short current pulses (Figure 2) with a repetition rate of 18.1 ± 1 pulses per second. Amongst the different proposed IEC standard pulse waveforms (Figure 4), the waveform that is the closest to the X26 waveform is the half wave sinusoidal waveform. We will then adjust this half sinus waveform to the X26 waveform.

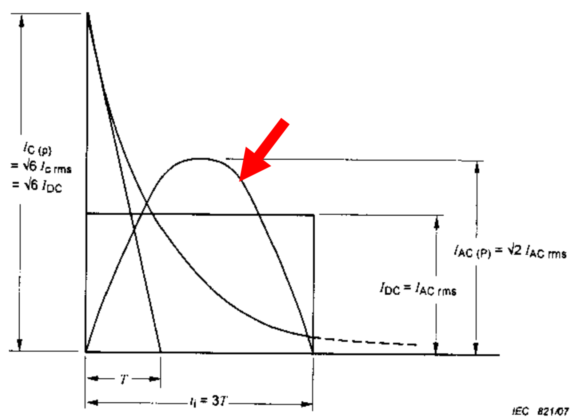


Figure 18 – Rectangular impulse, sinusoidal impulse and capacitor discharge having the same specific fibrillating energy and the same shock duration

Figure 4 Standard pulse waveforms (from IEC 60479-2)

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[5] These two documents are not yet considered as "International Standards":

- IEC 60479-1 is a "Technical Report Type 2", it is a "prospective standard for provisional application" because there is an urgent requirement for guidance on how standards in this field should be used to meet an identified need. It focuses on the effects of low frequency sinusoidal current (15-100 Hz) and DC current.
- I/IEC 60479-2 is a "Technical specification", published when the subject is still under technical development, or when there is the future but no immediate possibility of an agreement for publication as an International Standard. It focuses on the effects of higher frequency sinusoidal current (100-10000 Hz) and current pulses.

Figure 5 Peak amplitude (2 A) and duration (60 µs) of a half wave sinusoidal waveform (white dotted line) that corresponds to the current generated by a typical X26 device (A04, 250 Ω)

Figure 5 shows a half wave sinusoidal waveform that is adjusted to the current waveform generated by a typical X26 device in a 250 Ω load. This device (A04) has characteristics close to the average characteristics found in the NTS report: peak current of 3.387 A (average 3.408 A) et net current of 2.08 mA (average 2.26 mA). The two parameters of the half wave sinusoidal waveform are the amplitude (2 A) and duration (60 µs). This duration is close to the 70 µs duration used by Stratbucker et al.[6]

The half wave sinusoidal waveform is an approximation of the X26 waveform, it underestimates the energy contained the X26 pulse because it ignores the fast initial oscillations as well as the trailing edge of the Taser pulse.

To apply the IEC 60479-2 charts, the effective current $I_{\text{AC rms}}$ is computed according to the following formula:

$$I_{\text{AC rms}} = 2\text{ A} / \sqrt{2} = 1{,}414\text{ A} \qquad (1)$$

The next step is to convert the Taser current into the equivalent 'body current" which is the standard way of representing current in the IEC charts. The following Table gives the "Heart-current factor" *F* for different current paths. Since police officers are advised to

[6] Stratbucker et al. Cardiac Current Density Distribution by Electrical Pulses from TASER devices Proceedings of the 28th IEEE EMBS Annual International Conference,p :6305-6307, 2006

Table 3. Heart current factor *F*. From IEC 60479-1

Table 5 – Heart-current factor *F* for different current paths

Current path	Heart-current factor *F*
Left hand to left foot, right foot or both feet	1,0
Both hands to both feet	1,0
Left hand to right hand	0,4
Right hand to left foot, right foot or to both feet	0,8
Back to right hand	0,3
Back to left hand	0,7
Chest to right hand	1,3
Chest to left hand	1,5
Seat to left hand, right hand or to both hands	0,7

shoot at the torso, we will consider a site of current injection in the "chest"[7], which corresponds to a heart-current factor of F=1.5 to compute the corresponding "body current" $I_{B\ rms}$:

$$I_{B\ rms} = 1{,}5 \times 1{,}414 = 2{,}12\ \mathrm{A} \tag{2}$$

Finally, the repetitive nature of the current pulses (here, 18.1 $\pm$ 1 pulses per second) must be taken into account because:

> *"Bursts of current through the heart that are separated by less than the period of a normal heart beat (less than approximately 1 s between consecutive bursts) can create disturbances in the heart with cumulative effects. These cumulative effects can lead to ventricular fibrillation even though each burst of current in the series is significantly lower than the fibrillation threshold for ventricular fibrillation applicable to each single bursts of current occurring alone. ... The threshold for ventricular fibrillation applicable to the second burst of current can be as low as approximately 65% of the threshold applicable to the first burst. This process can continue until the threshold reaches a minimum after several bursts. The minimum threshold reached can be only 10% or less of the threshold applicable to the first current burst."*[8]

[7] The RCMP Use of the Conducted Energy Weapon (CEW) report from June 12, 2008 (Chair, Paul E. Kennedy) showed that at least one dart impacted the chest or abdomen in 46.1% of reported cases.

[8] IEC60479 Part 2, section 9

Table 4. Reduction of ventricular fibrillation threshold due to repetitive firing. From IEC 60479-2

Table 1 – Example of estimate for ventricular fibrillation threshold after each burst of current in a series

Burst of current in a series of bursts separated by less than 1 s, where the first current burst is in the AC-3 or DC-3 region of Figure 20 or Figure 22	Example estimate of the ventricular fibrillation threshold after each burst of current in a series %
First current burst	100
Second current burst	65
Third current burst	42
Fourth current burst	27
Fifth current burst	18
Sixth current burst	12
Seventh and subsequent current bursts	10 or less

This reduction in the ventricular fibrillation threshold (this threshold corresponds to the current intensity that will cause cardiac arrest) may have important implications and its significance must be fully understood before proceeding further with the application of IEC60479-2.

According to Han et al.[9] and Weirich et al.[10], this threshold reduction occurs when current pulses trigger "extrasystoles" (extrasystoles are premature contractions of the heart).

Cao et al. have shown that Taser discharges can trigger these extrasystoles in a man with an implanted pacemaker[11]. In experiments carried out in 6 pigs, Nanthakumar et al. have shown that of 94 thoracic Taser discharges, 74 triggered extrasystoles[12]. Walter et al. have found in a pig model that thoracic Taser discharges triggered extrasystoles in all animals[13].

The hypothesis that Taser impulses can trigger extrasystoles is realistic, especially when the Taser barbs impact in the precordial region (over the thorax, near the heart). Even if it corresponds to a "worst case" scenario, it should be applied for the evaluation of Taser's safety.

Cao et al.[9] found that an extrasystole was produced by every fourth Taser discharge, which corresponds to about 4 extrasystoles per second. The time interval between each extrasystole is less than one second, which is not long enough for the electrophysiological disturbances to subside and this reduces the ventricular fibrillation threshold by 35% after each extrasystole.

After 7 extrasystoles (about 2 seconds), the threshold is reduced to 10% of its initial value and it will remain at that level for subsequent pulses. We will thus apply a repetitive threshold that is

[9] Han J et al. Fibrillation threshold of premature ventricular responses. Circ Res vol 18, p :18-25, 1966.

[10] Weirich et al. Ventricular fibrillation of the heart induced by electrical current. Revue générale de l'électricité. vol. 11, pp :833-843, 1985

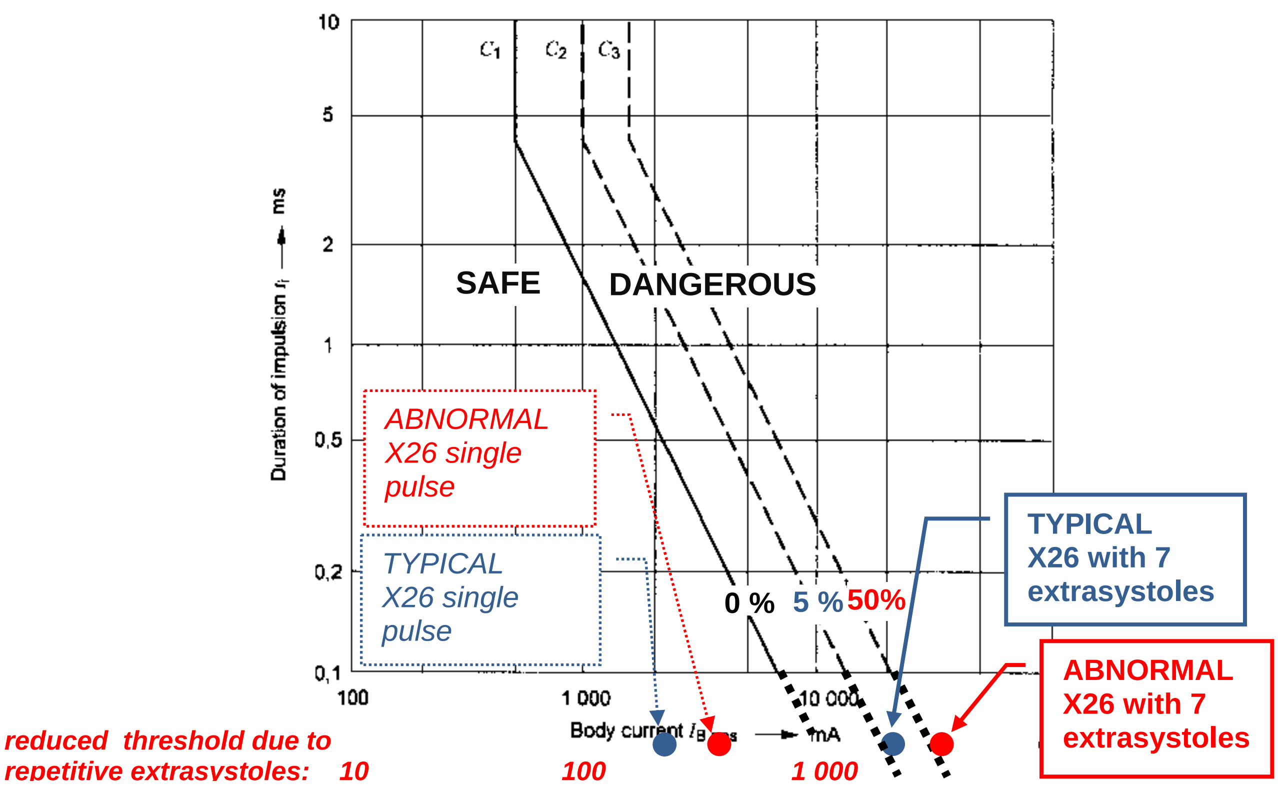
[11] Cao M et al. Taser-induced rapid ventricular myocardial capture demonstrated by pacemaker intracardiac electrograms J Cardiovasc Electrophysiol. 2007;18(8):876-9. *Note: the pacemaker stored in its memory the electrical signals recorded in the heart. It is possible that the pacemaker distorted the current distribution and contributed to triggering the extrasystoles, but it has been argued that the impedance between the leads and case of the pacemaker was too high to distort the current distribution*.

[12] Nanthakumar K, et al. Cardiac electrophysiological consequences of neuromuscular incapacitating device discharges. J Am Coll Cardiol. 2006 15;48(4):798-804.

[13] Walter RJ et al. TASER X26 Discharges in Swine Produce Potentially Fatal Ventricular Arrhythmia. Academic emergency medicine. 2008; 15:66–73, 2008.

reduced to 10% of the single pulse threshold. Figure 6 shows the threshold for ventricular fibrillation as a function of the intensity and duration of the current pulses (from IEC60479-2). Because the measured impulse durations are shorter than the lower limit of the chart, we have to extrapolate below the chart. Also, a new current intensity scale (in red, italics) was added to account for the important reduction of threshold due to repetitive firing. We observe that:

- for a typical X26 (A04; pulse duration: 0.060 ms; body current: 2.12 A) the probability of ventricular fibrillation is estimated at about 5% (if Taser pulses trigger extrasystoles);
- for an abnormal X26 (A03; pulse duration: 0.060 ms; body current: 3.60 A; see Figure 7) the probability of ventricular fibrillation is estimated at about 50% (if Taser pulses trigger extrasystoles and the high current pulses persist). For the repeated measurement on the same device (after 19 pulses, see Figure 3A), the body current is 2.86 A (2.7 A x 1.5 x 0.707) and the VF probability is near 50%.



The curves indicate the probability of fibrillation risk for current flowing through the body from the left hand to both feet. For other current paths, see 5.9 in IEC 60479-1.

Below C_1:	no fibrillation;
Above C_1 up to C_2:	low risk of fibrillation (up to 5% of probability);
Above C_2 up to C_3:	average risk of fibrillation (up to 50% of probability);
Above C_3:	high risk of fibrillation (more than 50% probability).

Figure 20 – Threshold of ventricular fibrillation

Figure 6 Threshold for ventricular fibrillation as a function of the intensity and duration of the current pulse (from IEC60479-2). A new current scale (in red, italics) was added to account for the reduction of threshold due to the possible repetitive triggering of extrasystoles.

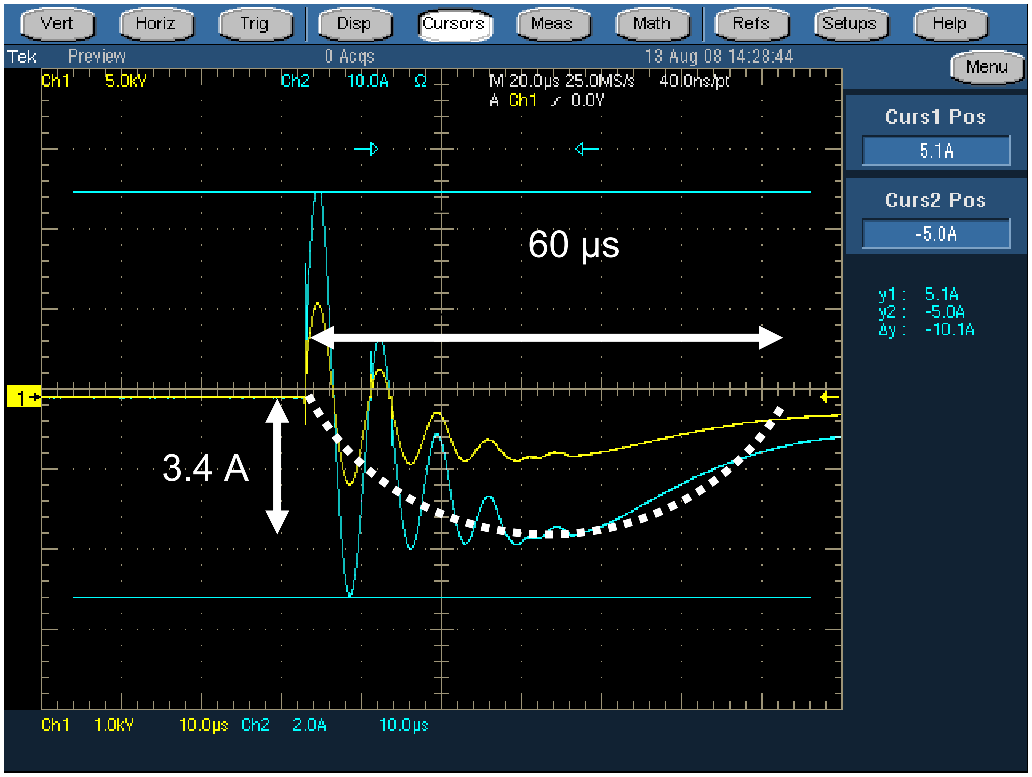


Figure 7 Peak amplitude (3.4 A) and duration (60 µs) of a half wave sinusoidal waveform (white dotted line) that corresponds to the current generated by an abnormal X26 device (A03, 250 Ω). The corresponding body current is = 3.4 A x 1.5 x 0.707 = 3.6 A.

3 Discussion

The above safety analysis is based on a strict application of the IEC60479 Technical Specification, but it has the following limitations:

Factors that underestimate the risk:

- The state of health of the subject is not taken into account. IEC Standards are based on extrapolation of experiments carried out in healthy animals. They do not specifically consider factors such as coronary artery disease, myocardial infarction and other diseases that increase susceptibility to cardiac arrhythmias and that are associated with an increased fatality rates after Taser discharges[14].

[14] Strote J, Range Hutson H. Taser use in restraint-related deaths. Prehosp Emerg Care. 2006; 10(4):447-50.

- Indirect effects that are mediated by the increased tonus of the autonomic nervous system by the Taser discharges are not taken into account: respiratory effects, electrolyte imbalance, etc.
- The half wave sinusoidal waveform underestimates the energy contained in the X26 waveform.

Factors that overestimate the risk:

- The probability of triggering extrasystoles that lower the ventricular fibrillation threshold is not absolute. Nanthakumar et al.[10] have reported a 79% rate of triggering extrasystoles (capture), but this can be much lower, especially if the barbs impact away from the heart. Valentino et al [15] have shown in a porcine model that ventricular capture rates are high when the current path traverses the cardiac region.
- The intermittent nature of these elevated discharges: the four X26 devices that produced abnormally high currents at 250 Ω, also produced current values within the limits of the manufacturer specifications when connected to other loads. This might be explained by the lack of a previous "spark test" before the measurements at 250 Ω.

The reduction of ventricular fibrillation threshold due to repetitive extrasystoles is an important aspect of our electrical safety analysis. Going indirectly from a normal cardiac rhythm to ventricular extrasystoles and finally to ventricular fibrillation requires less current than going directly from a normal cardiac rhythm to fibrillation. This reduction of threshold due to repetitive extrasystoles is not taken into consideration by the proponents of the Taser device who base their safety analysis[16] on the effects of a single pulse (Green model, Peleska model), or consider a stream of pulses as a sinusoidal current. Thus, Kroll[17] characterises the X26 as a point with an average current of 1.9 mA and a frequency of 19 Hz on a chart showing thresholds as function of frequency and current intensity, however, this approach is not applicable since alternating current has an average intensity equal to zero. Panescu[18] specifically refers to IEC60479 Part 2 to compute a safety margin of 50, he uses a charge value *Fq* = 5000 μC that causes a 50% probability of ventricular fibrillation, however that charge value is valid only for an impulse duration of 2 ms, the value of *Fq* decreases to 2000 μC for an impulse duration of 0.1 ms because the ventricular fibrillation thresholds from IEC60479-2 are based on a combination of critical charge and energy (also, safety thresholds computed with respect to a 50% probability of ventricular fibrillation are misleading).

However, the strict application of IEC60479-2 Technical Specification using the extrasystole hypothesis seems to overestimate the risk since the observed fatality rates in real-life situations appear to be significantly lower than those predicted by IEC60479-2. What are the reasons for this divergence? The threshold reduction may not be as important as indicated in IEC60479-2, even if extrasystoles are triggered; or extrasystoles may rarely be triggered in practice because

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[15] Valentino et al. Taser X26 Discharges in Swine: Ventricular Rhythm Capture is Dependent on Discharge Vector. J Trauma 2008;65:1478 –1487.

[16] http://www.taser.com/research/Science/Pages/CardiacSafety.aspx

[17] Kroll MW, Crafting the perfect shock. (2007) Spectrum, December, pp :27-30

[18] http://www.taser.com/research/Science/Pages/TASERECDDistrubition.aspx

barbs impact away from the heart. Alternatively, the barbs may fail to penetrate the skin thereby decreasing the delivered current.

Even if no threshold reduction is applied, Figure 6 still shows that the safety factor for the typical X26 is about 4.4 (the current must be multiplied by 4.4 to reach the 0% fibrillation threshold), whereas that of the abnormal X26 is 2.6. Considering that fibrillation thresholds are not immutable because of human variability, these safety factors are not sufficient to ensure that the probability of fatalities always remains at zero.

4 Recommendations

Considering that a strict application of the risk assessment method described in the IEC60479-2 Technical Specification suggests that X26 Tasers with intermittent, abnormally high output can have a significant probability of cardiac arrest when the barbs impact the chest in the vicinity of the heart and the current impulses trigger premature cardiac contractions, we recommend:

- A moratorium on the use of older X26 devices (manufactured before 2005).
- Further study on the electrical characteristics of a representative sample of Taser X26 devices already in use in Canada and the US. This study should specifically investigate the output of older *vs* newer devices and the occurrence of irregular or variable discharges using a standardized testing protocol such as the one used by NTS.
- The testing protocol should include continuous, high resolution recordings lasting at least 2 seconds to measure possible changes in a series of 36 or more individual current pulses during the initial firing sequence and should evaluate the effects of “spark testing”. This will determine whether the aberrant high output continues after the initial pulse and what effect “spark testing” has on the subsequent output of X26 devices.