Stray Voltage and Milk Quality: A Review

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SYNOPSIS

This paper provides a comprehensive review of research conducted to investigate the effects of electrical exposure (stray voltage) on mastitis, milk composition, and dairy cow health. Although the perception that stray voltage can result in increased SCC and incidence of mastitis and suppress dairy cows' immune system, there is a large body of research that clearly indicates that at levels of voltage exposure typically used as regulatory limits (1 Volt at cow contact locations, or 2 mA of current flow through a cow) will not result in increased SCC or the incidence of mastitis. This research also supports the recommendations of the group of national experts (1) that voltage exposure less than 2 V (assuming low contact resistance) to 4 V (assuming more typical contact resistances on farms) will not result in reduced milk production or increased mastitis on dairy farms.

Introduction

The term stray voltage describes a special case of voltage developed on the grounded neutral system of a farm and is defined as less than 10 volts (V) measured between two points that can be contacted simultaneously by an animal (1). Some level of voltage between grounded metallic objects and the earth will always be present as a normal consequence of the operation of properly installed electrical equipment. Contact voltages under 10 V are not lethal to cows or people. Contact voltages in excess of 10 V may be indicative of a major electrical fault that could electrocution hazard on a farm, and are treated differently from the low-level contact voltages defined as stray voltage. The terms 'earth current' or 'ground current' are sometimes used to refer to stray voltage. These currents flowing in the earth or on grounded metal objects will only affect cows if sufficient voltage potential is developed between cow contact points and the same cow contact measurement methods should be used to assess these currents.

Stray voltage first came to the attention of the North American Dairy professionals in the 1970's following research conducted in New Zealand in the 1960's (2). Early work included surveys of dairy managers to determine their perceptions of the effects of stray voltage on dairy cows. Among the symptoms attributed to stray voltage were an increased incidence of mastitis and elevated bulk milk somatic cell counts (SCC), reduced milk production, changes in milking performance, and changes in animal behavior (3). There has been a considerable body of research that has tested the hypotheses that stray voltage can cause these symptoms. This paper will provide a brief overview of the studies done on behavioral responses to stray voltage exposure and a detailed review of studies that were designed with the primary objective to investigate the effects of stray voltage exposure on mastitis as well as those behavioral studies that also included measures of mastitis, such as individual cow or group SCC and other physiological responses related to stress.

Basic concepts of voltage, current, and resistance

Because animals respond to the current produced by a voltage and not to that voltage directly, the source of the voltage must be able to produce current flows greater than the threshold current needed to elicit a response from an animal (1). The relationship between voltage exposure and current conducted through the animal is described by Ohms Law. Ohm's law expresses the relationship between voltage, current and resistance in an electrical circuit:

Current = Voltage / Resistance or Amps = Volts / Ohms (Eq. 1)

This simple relationship has been a source of much confusion and resulting controversy in the stray voltage debate. Ohms law indicates that if the voltage (across animal contact points) is increased the current flowing through the animal will increase. Likewise if the resistance (of contact points) is increased the current flowing through the animal will decrease. The current measure used in most studies is milliamps (mA) or 1/1000th of an amp. The standard measurement circuit used for field investigations uses a 500 Ohm resistor to simulate the combined resistance of a cow's body <u>plus</u> a conservative estimate of the resistance of the two contact points (cow+contact, or shunt resistor). A cow contact voltage of 1 V is equivalent to a cow contact current of 2 mA when using a cow+contact resistance of 500 Ohms.

While the contact voltage is often used to describe animal exposure conditions, it is the resulting current flowing through animals' bodies that determines the 'dose' and the resulting type and degree of nerve stimulation. It is critically important to use a realistic value of animal resistance to relate voltage exposures to the level of current conducted through an animal and the resulting effects on nerve stimulation, sensation, and behavioral reaction. A competent field investigation will include voltage measurements at cow contact locations measurements both with and without (open circuit) a shunt resistor. These two measurements are required to determine the 'source resistance' of the electrical parts of the circuit [NB: source resistance is different from the cow contact resistance (1)].

The body resistance of animals has been measured in several studies. Measures of an animal's body resistance depends on the pathway between the 2 contact points (e.g. muzzle-hoof or hoof-hoof) and the way in which the contact is made including factors such as the area over which the contact is made, pressure applied to the contact, and use of conductive liquids or gels on the measurement connection. The lowest body resistance values have been reported when the skin of the animal was pierced using needles. The next lowest category of body resistances include measurement electrodes affixed to shaved patches of skin. The majority of body resistance measurements have been made with cows coming into contact with metallic devices. Some of the most common examples include standing on a metal plate or mesh, metallic bit in the mouth, or a metallic clip applied to the nose.

Contact resistances are the most difficult value to predict in real-world farm situations. Fewer studies have been done to characterize real-world contact resistances. However it is clear from these studies as well as physical principles that real-world contact resistances have enormous variability. The lowest contact resistances would be expected if a clean, wet body part (such as a cow's muzzle) comes into contact with a clean, wet, metallic object with a substantial mutual contact area and substantial contact pressure. The accepted practice by researchers and regulators has been to assume worst-case (lowest practical values) for contact resistances. Studies done to measure more typical body + contact resistances that would occur on farms (1, 4, 5) have shown that 500 Ohms is a reasonable value to use in a measurement circuit to estimate the current that would flow through a cow's body. Although the resistance of the cow's body is typically less than 500 Ohms for the muzzle to hoof pathway (other pathways have a higher resistance,) it has been shown to be a 'worst case' or minimum resistance value for the combination of a dairy cows body + real-world contact resistance in the farm environment.

Impedance is a measure of the resistance to current flow in alternating current (AC) circuits and includes elements of resistance, capacitance and inductance. There are some situations in which the capacitance and inductance are important, e.g. when considering high frequency AC circuits. Impedance is a more technically specific term for AC circuits but resistance will be used here for simplicity unless otherwise noted. Voltage and current flow in AC circuits alternates between positive and negative values in a sinusoidal form 60 times per s (60 Hz,) or 50 Hz in European power systems. The most common way to express voltage and current in AC circuits is with the root-mean square (rms) average over the alternating cycle. References to voltage and current will be expressed as 60 Hz, rms averages in this paper unless otherwise noted.

The Bio-mechanics of Nerve Stimulation

The bio-mechanics of electrical nerve stimulation in humans has been widely studied for beneficial medical purposes (cardiac stimulators and pace-makers, relief of chronic pain, and muscle contraction for therapeutic purposes) as well as to set thresholds to avoid pathological exposures that may result in injury or death (6). This body of literature has been used as the basis to establish cause-effect relationships between various types of voltage and current exposure and behavioral responses in dairy cows. Both sensory neurons (producing sensations) and muscle neurons (producing muscle contraction) can be elicited with electric currents conducted through the skin. Sensory effects are elicited with lower current dose than are motor effects. Nerve stimulation is characterized by a current threshold. Current applied below the threshold will not produce nerve excitation, and hence no sensation, motor response, or behavioral response can occur. At the current level just above the threshold of sensory nerve excitation the current will be perceptible but not painful. As the current level is increased above the sensory nerve threshold motor neurons will begin to activate and involuntary muscle contraction begins to occur. This lower margin of muscle contraction is not generally perceived to be painful. Pain can be experienced at as current exposures are increased further due to both increased sensory stimulation and more intense muscle contraction. Behavioral responses are the result of nerve stimulation that elicits a sensation and/or muscle contraction in an animal.

Review of Research on Behavioral Responses to Voltage exposure

The most common type of research on stray voltage has been to identify the lowest thresholds of voltage exposure that could result in nerve stimulation and behavioral responses. An extensive review of the research literature on the behavioral responses of dairy cows to 60 Hz voltage exposure was conducted for the Ontario Energy Board as part of the process of developing rules and regulations in Canada (7).

Levels of current exposure just above the nerve excitation threshold will result in mild behavioral reactions in cows, such as the blink of an eye, which tend to become less pronounced over time as animals become accustomed to the sensation. As current exposure is increased above this threshold, behavioral responses in cows become more pronounced and more persistent, indicative of annoyance, pain or involuntary muscle contraction (twitches.) A summary of research results on individual animal behavioral response thresholds is shown in Figure 1. These studies all applied known levels of current, in an ascending series, through an individual cow until a pre-defined behavioral response was observed and thus allowed for the specification of a response threshold for individual cows (8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23).

During experiments conducted on a sample of 355 cows, the first behavioral responses noted by the researchers fell between 2.5 mA for the 5% most sensitive cows and 8.5 mA for 95% of cows, with the 50th percentile at 4.8 mA. Many of the research groups noted rapid acclimation to the current levels just sufficient to produce subtle behavioral responses and increased current exposure levels in order to obtain a more repeatable response, often noted by researchers as indicative of discomfort or involuntary muscle contraction. The threshold of involuntary muscle contraction would be expected to occur at higher current does levels than the threshold of sensory stimulation and would also be expected to be a more repeatable threshold indicator as acclimation would not reduce the reaction to the stimuli. The threshold of discomfort and/or involuntary muscle contractions for 125 cows fall between 3.5 mA for the 5% most sensitive cows and 11 mA for 95% of cows, with the 50th percentile at 6.5 mA. Thresholds for aversive response thresholds (primarily a delay to drink water) and those studies in which researchers identified thresholds at which cows appeared to be in pain (36 cows) fall between 5.5 mA for the 5% most sensitive cows and 16 mA for 95% of cows, with the 50th percentile at 8.5 mA. These results show remarkable repeatability and consistency in the response of dairy cows to 60 Hz current exposure across 15 separate experiments, by 9 research groups, across 31 years and two continents.

Transient and High Frequency and Exposure

In addition to the steady 60 or 50 Hz voltages developed by the use of electrical power, there are also transient voltages that may occur at higher frequencies. The responses to electrical exposures to alternating current with frequencies above 60 Hz have also been studied and are explained well by neuro-electric models (1, 8, 9, 18, 19, 24). Studies on high frequency current exposure clearly indicate that as the duration of a current pulse gets shorter (or the frequency increases above 60 Hz), more voltage and current is required to cause a behavioral response (Figure 2).

Momentary 60 Hz events can be generated by starting electric motors. The starting current of the motor and the resistance of the farm neutral determine the magnitude of a motor starting transient for 120 V motors and the primary neutral for 240 V motors. Motor starts typically produce multiple cycle 60 Hz transients. The main cause of short duration electrical pulses on farms is improperly installed electric fences and electrified crowd gates. These devices are designed to produce a powerful electric impulse that is used to control animal behavior. Improper installation of these devices can cause these pulses to appear in unintended areas on the farm. The other most common source of high frequency events are switching transients that occur when electrical equipment is turned on or off. These high frequency pulses decay quickly, do not travel far from their source, and extremely rarely reach exposures levels that are problematic to animals.

Review of Research on Stray Voltage, Mastitis and Stress

In an early experiment conducted by USDA scientists to investigate the endocrine response of six cows exposed to 5 mA of current applied through EKG patches applied to the skin of the udder and hock starting 10 min. prior to milking and continuing through the milking and continuing for a total of 20 min. (13). Cows were exposed to both continuous current and to current applied in an intermittent pattern (5 of every 30 s). Prolactin concentration decreased and milk yield decreased by 11% to 17% by intermittent current but neither was reduced by continuous current. Neither treatment appeared to have an effect on norepinephrine or prolactin levels. Both exposures increased oxytocin responses. The authors noted that cows seemed to adapt to the stimulation.

A team of researchers at the University of Minnesota measured the electrical resistance of milking machine components and found milk hose resistances ranging from about 30,000 Ohms to 80,000 Ohms depending on the milk flow rate (26). The minimum resistance from the claw through the cow to the floor was 3,000 Ohms. It was estimated that 25 V to 50 V across this system would be required to obtain perception level currents through a cow.

Six non-pregnant cows were milked while being exposed to current levels of 0 mA, 4 mA or 8 mA, applied from udder to four-hooves (12). Each treatment was applied during the entire milking period with an intermittent pattern (5s on, 5 s off), twice per day for 7 days. Each cow was exposed to all three exposure levels. Cows showed behavioral responses to the 4 mA and 8 mA treatments. There was an increase in blood cortisol concentration, a trend of increased, prolactin, and oxytocin concentrations at the 8 mA treatment level. There was no difference in SCC, fat, protein, milk yield, residual milk peak milk flow rate, time to achieve peak milk flow, or milking duration between any of the treatments.

Six non-pregnant Holsteins were exposed to 4 mA (60 Hz rms) of current 10 s prior to udder preparation and during the entire milking period at every-other morning milking on 6 consecutive days (12). Current was applied through sub-dermal electrodes placed in the lumbar region of spinal column approximately 15.2 cm apart (targeting the sensory nerves to the udder). Current exposure resulted in an increase in heart rate, increased carotid arterial blood pressure, and increased mammary blood flow.

Eight pregnant Holstein cows from 16 to 20 weeks in second lactation were exposed to 4 mA of current for 96 hr with current administered once every 4 hr in an intermittent pattern (30s on, 30s off for 5 min) using a semi-randomized exposure scheme (27). Current was applied through sub-dermal electrodes placed in the lumbar region of spinal column approximately 15.2 cm apart (targeting the sensory nerves to the udder). Some behavioral changes were noted during the first 30 s of exposure and a slight (1%) but not statistically significant reduction in milk yield. There were no significant differences in SCC, milk fat, milk protein, feed intake, or water consumption.

Seven cows were exposed to 3.6 mA and 6 cows to 6.0 mA applied through EKG patches applied to shaved skin on the right rear hock and right front knee during milking (2x) with an intermittent pattern (5 s on, 25 s off) for 7 days (28). The number of behavioral events increased with a greater increase in the 6.0 mA group. One cow had to be removed from the 6.0 mA group because of severe behavioral responses. Heart rate was elevated (+3 beats/min) only in response to the initial 1 min exposure during udder preparation. Time to peak oxytocin response was delayed in the 3.6 mA group. Peak milk flow increased slightly and peak prolactin and area under prolactin response curves increased similarly for both groups. Wisconsin Mastitis Test scores, milk yield and milking duration and were not affected. The author concluded that any negative effects of electrical shock on milk production or mammary health most likely are not related directly to shock (physiological responses to shock were minimal and milk yield was maintained), however, the behavioral responses to 6 mA would result in management problems.

Six cows were exposed to 0 mA, 4 mA, or 8 mA of current applied from udder to hooves during 14 consecutive milkings using a changeover design over three consecutive 1-wk periods (29). Current was applied as 60 Hz square waves of 5 s duration applied every 30 s and began 5 min before milking and continued until milking unit removal. Behavioral responses to current were noted but decreased with time. Blood cortisol concentration increased and oxytocin release was delayed for the 8 mA exposure. Neither treatment affected SCC, milk yield, protein, fat, milking duration, peak milk flow rate, duration of peak milk flow, residual milk yield, or prolactin.

Seven cows were exposed to an ascending series of 60 Hz currents of 0, 2.5, 5.0, 7.5, 10, then 12.5 mA, applied through EKG patches applied to shaved skin on the right rear hock and right front knee (14). Currents were applied for 10 s intervals. As the current dose increased, cows became more agitated and two cows were not shocked at 12.5 mA due to severe behavioral responses. Heart rate immediately after shock increased at 10 mA and 12.5 mA treatments while prolactin, norepinephrine, and glucocorticoids were unaffected. Epinephrine doubled in two exceptional cows at 10 mA. Dramatic behavioral responses displayed by cows at the higher current exposures were not correlated with significant or prolonged physiological responses and electrical exposure was not considered a reliable way to induce ‘stress’ in cows.

Fourteen multiparous cows (8 second, 5 third, 1 fourth lactation) and fourteen first lactation cows were enrolled in an 7-week experiment with 14-day pre-treatment, 21-day treatment, 14-day post-treatment periods (30). Cows were randomly assigned to 0 V, 0.5 V, 1 V, 2 V or 4 V treatment groups. The current flow path was from the mouth (drinking cup) to rear hooves (metal grid). There were no statistically significant differences in SCC or milk conductivity within each treatment voltage across periods or within each period across voltages for either group of cows. Some cows developed clinical mastitis during the experiment; 5 in the pre-treatment period, 4 during treatment (1 @ 0 V, 0 @ 0.5 V, 1 @ 1 V, 1 @ 2 V, and 1 @ 4 V), and 4 during post-treatment. The incidence of mastitis was evenly distributed across control and treatment groups with no consistent pattern between clinical mastitis and voltage levels, leading the authors to conclude that both the incidence of the disease and type of infecting bacteria were not related to voltage level. There were also no significant relationships found between level of voltage and body temperature or reproductive problems.

Alternating currents were delivered to lactating cattle through the milk during milking (31). The current flow path was between electrodes placed at the top of each short milk tube to a metal grid on which the cows' rear hooves stood. In trial 1, four voltage levels were selected for the first lactation (0, 2, 4, and 8 V) and 8 multiple lactation (0, 4, 8, and 16 V) cows using a Latin square design on four over consecutive milkings. Behavioral changes were noticeable at voltages greater than and equal to 4 V for first lactation cows and 8 V for multiple lactation cows and corresponded to average currents of 4.1 mA (range 2 to 7 mA) for first lactation cows and 9.1 mA (range 4 to 14 mA) for multiple lactation cows. Only at 8 V for first lactation cows and 16 V for multiple lactation cows did some cows kick off machines. Currents associated with kicking the machine off were 5 to 12.5 mA for first lactation cows and 8 to 18 mA for multiple lactation cows. There were no consistent significant differences in milking duration, milk yields, or composition (milk fat, milk protein, or somatic cell counts) of primary milk and residual milk. For the 8 multiple lactation cows, milk protein increased by 0.1% for the 4 V, but not the 8 V or 16 V treatments, and protein in residual milk increased by 0.2% at the 4 V and 0.1% at the 8V, but not at the 16 V treatment. Fat in residual milk also decreased by 1.4% for these cows at the 4 V, but not for the 8 V or 16 V treatments. Milking durations were generally longer (0.4 min to 1.0 min, with an increasing trend with voltage levels) but these differences were not statistically significant.

A second trial was conducted in which currents selected were just below those that caused cows to kick milking machines (5 mA for first lactation cows and 8 mA for multiple lactation cows) and was delivered for six consecutive milkings to 8 first lactation cows and 8 multiple lactation cows in the same manner as in the first trial (31). No undesired behaviors were observed for either group of cows. There was no significant change in SCC, milk yield, milk fat, or milk protein. SCC was lower for the multiple lactation cows and higher for the first lactation cows when currents were applied, but neither was significantly different. Milking duration was 1 min less in first lactation cows but did not differ in multiple lactation cows. Serum cortisol concentrations were lower in multiple lactation cows 2 min prior to and 6 min after milking began, and were similar at other times. Milk yield showed a slight (0.1 to 0.5 kg) but not significant increase in both groups of cows during milkings in which current was applied. The authors concluded that a voltage greater than 125 V on the milk line a voltage greater than 5 V on the claw of the milking cluster would be required to produce 5 mA of current through the milk to the cow, and that the milking machine does not appear to provide a significant risk because of the magnitude of the voltage and currents needed to create economic effects.

Four groups of 10 Holstein cows each were exposed to 0 V, 1 V, 2 V, or 4 V between waterers and a metal grid throughout an entire lactation (32, 33). Cows could not drink without placing their front hooves on the metal grid. The test pens had 10 cows in them at all times. Herd cows or 'placeholders' were replaced by test cows as fresh cows became available from the herd. All of the test cows completed their entire lactation in the treatment pens. Although there were some behavioral changes on the first day of exposure, feed and water intakes of test cows were not affected by any of the voltage treatments. One cow and 1 heifer refused to drink from their water bowls for 36 hrs when bowls were electrified at 4 V. All other cows that were subjected to voltage on the water bowl drank after some delay during the first 24 hrs. The delay was directly proportional to the voltage level. However, within 48 hr, those cows were consuming the same amount of water as during the pre-test period. One first lactation cow, out of a total of 51 cows placed in the 4 V pen, had to be removed. This cow was a herd cow. Her milk yield decreased rapidly, and she was not consuming grain during her first 36 hr in the pen. This was the only cow that had a water consumption problem. Milk yield for the full 305 day lactation test group showed no significant differences between groups exposed or unexposed to and of the voltage treatment levels. SCC, milk fat and milk protein in the test cows showed no significant differences between groups exposed or unexposed to voltage. (Gorewit, 1992a) Voltage treatments did not significantly influence cow health or reproductive performance as measured by mastitis, hoof problems, changes in body weight, days to first breeding, days open, and services per conception, calving intervals, visible abortion, and calves born dead.

Three switch back experiments (30 cows each) were conducted to determine the effects of the three different levels of voltage applied from muzzle (water bowls) to hooves (the cow platform) (34, 35). The 112 day experiment was divided into four, 28-day periods and cows were randomly assigned to 6 treatment groups with voltage and no-voltage treatments applied in different patterns across the four week periods. A continuous low-level voltage was interrupted by two, three-hr periods of higher levels at 5 am and 5 pm, to simulate higher loads during milking that occur on many dairy farms. The first experiment used 1 V with a background voltage of 0.3 V, the second experiment used 2.5 V with a background level of 0.75 V, and the third experiment used 5 V with a background voltage of 0.75 V. The parameters measured were: daily milk production, milking time, milk composition (% butterfat, % protein, % lactose and SCC), water consumption, and feed consumption. Dates of estrus and breeding were recorded and behaviors (urination, defecation, drinking, lying time, standing time and any abnormal behavior) of each cow were observed for 25% of each day. The effects of each outcome variable were analyzed for effect during the treatment period as well as for carryover effects occurring 1 or 2 periods after the treatment. Exposed cows had significantly higher milk fat percentage (31.2 versus 30.6 kg/cow/day) in the first experiment (1 V). Milking time was longer (8.5 versus 8.3 min) for the second experimental group (2.5 V). There was a carry-over effect on milk yield two periods after the treatment for the third group (5 V). In addition, less water (97.6 versus 100 L/cow/day) was consumed by the treatment group. No differences in SCC were detected at any of the exposure levels, nor were any carryover effects observed. The authors concluded that exposures up to 5 V in well managed tie-stall dairy operations were unlikely to cause observable changes in cow milk production or behavior.

Sixteen Holstein cows with a history of subclinical mastitis (cultured positive for *Staphylococcus aureus*), were used to determine exposure to steady state voltages could trigger clinical mastitis or result in compromised health or reduced immune function in cows predisposed to mastitis (36). Cows were divided into four treatment groups of four cows each with constant voltage treatments of 0 V, 1 V, 2 V, and 4 V applied continuously between water bowls and metal floor mats for seven days. Water intake, milk yield, feed consumption, milk composition, somatic cell counts, and milk microbiology and cortisol were monitored before during and after seven day exposures to voltages. Blood samples were taken from each cow every other day throughout each period prior to milking via tail vein venipuncture. Samples were allowed to clot and serum was isolated. Serum was analyzed for; 1. Bovine Panel (sodium, potassium, chloride, bicarbonate, anion gap, urea, creatinine, calcium, phosphate magnesium total protein, albumin, globulin, glucose, alkaline phosphatase, ast/PSP, SDH, hGGT, indirect, direct and total bilirubin, ck, iron, and TIBC), 2. Immune gamma-globulins: IgG, IgA, IgM, and 3. Blood serum cortisol. Animals perceived voltages as evidenced by delays in drinking, which increased with voltage. There was no significant difference in milk production, milk composition, SCC, feed consumption, blood chemistry, milk microbiology and serum cortisol when the treatment period was compared to the one week pre and post treatment periods. The number of *Staph. aureus* infected quarters did not increase across treatments. The quarters showing high somatic cell counts were consistently high throughout the experimental periods and those non infected quarters within those animals remained uninfected with *Staph. aureus* organisms throughout the experiment. A non-significant trend existed for higher cortisol levels as voltage levels increased (+1 ng/mL @ 4 V). The absolute level of milk production, somatic cell counts, milk fat and protein, and IgM levels were higher in the two volt group but these differences were also present in the pre and post treatment periods and the authors noted that this was likely caused by the subclinical *Staph. aureus* infections present in the cows at the start of experimentation.

Sixteen lactating Holstein cows, eight cows receiving bovine somatotropin (bST) and eight bST free cows, were exposed to 0 V, 1 V, 2 V, or 4 V applied from a metallic water bowl to a metallic plate under the rear hooves for a period of 7 days (37). Microbial analysis revealed that no cows were infected with *Streptococcus uberis* at the beginning of the experiment. All cows were exposed to *Strep. uberis*, as a post teat dip after milking. Milk samples were aseptically collected and cultured for bacteria. Voltages did not significantly influence somatic cell counts, feed intake, water intake, milk yield, milk fat or milk protein. Out of the sixteen cows studied, no cows developed clinical mastitis. The authors concluded that steady state Voltages of up to 4 V, applied to water bowls, for 7 days, did not promote clinical mastitis in dairy cattle during or after direct exposure of live bacteria to teat ends and that bST treatment did not result in mastitis in cows subjected to these conditions. The authors noted that this experiment is supported our previous work that steady state levels of up to four volts on water bowls do not lower the immune resistance of cows, consequently making them more prone to mastitis and further demonstrates there is no physiological causal relationship between steady state stray voltage exposure of up to 4 volts and mastitis in dairy cattle.

Milking performance of cows subjected to electrical current during milking and two common milking machine problems were documented (38). The first experiment used 32 cows in a 2x2 factorial design with exposure to 1 mA of electrical current from front to back hooves during milking and a pulsation failure (no massage phase) as treatments. A second experiment used 16 cows in a 2x2 factorial design with exposure to 1 mA of electrical current from front to back hooves during milking and excessively aged milking machine liners as treatments. The main effect of current exposure was not statistically significant for milk yield, average milk flow rate, maximum milk flow rate, cow activity, and strip yield. The main effect of pulsation failure was significant for cow activity (- 5.8 weight shifts during a milking). The main effect of aged liners was significant for milk yield (+

2.2 kg), average flow rate (0.3 kg/min reduction), maximum flow rate (- 1.2 kg/min), and liner slips per milking (+26) The significance of some interactive effects appeared to indicate that current exposure had a mitigating effect on the changes caused by the milking machine problems. However these interactions were not consistent across experiments and in some cases were highly influenced by a few observations. This study adds further evidence to the body of literature showing that exposure to low-level step potential resulting in less than 1 mA rms of 60-Hz electrical current during milking is not a cause of cow discomfort or poor milking performance.

A series of experiments was performed to measure behavioral responses and changes in blood cortisol concentration of cows exposed to 60-Hz electrical current applied from front to rear hooves (21). The current flow pathway was between one front hoof and 2 rear hooves. The current exposure levels administered in an ascending series using 0.5, 0.75, 1.0, and 1.5 times the previously determined behavioral reaction threshold for each cow resulting in currents ranging from 1 mA to 5.25 mA. The time between current exposures was 10 min. Cortisol levels did not increase in response to 5-min current exposure at levels up to 150% of the behavioral reaction threshold but serum cortisol concentrations did increase in response to hoof trimming. The authors concluded that these results confirm several previous studies indicating that behavioral changes are a more sensitive indicator of response to short-term electrical current exposure than blood cortisol levels.

Twelve mid-lactation dairy cattle were subjected to intermittent low electrical currents (1 mA +/-0.1 mA) from front to rear of stall for a period of 14 days (39). Twelve additional cows were housed in identical stalls with no treatment. Feed intake, water intake, milk production and rectal temperature were monitored daily and were unaffected by treatment. Behavioral measurements, including percentage of time lying and time to re-enter stalls after milking, were unaffected by treatment. Immune function was assessed by analyzing blood samples taken twice a week for thirteen different response variables. The measures for lymphocyte blastogenesis (concanavalin A and phytohemagglutanin mitogens), and oxidative burst (PMA-induced chemiluminescence) were chosen a priori as the best indicators of immune function response. Immunoglobulin production and interleukin 1 and 2 were also assessed. There was no statistically significant difference between control and treatment cows for any of the main response variables. The difference between the control and treatment cows was statistically significant for one of the secondary response variables (lymphocyte blastogenesis for *Staph. aureus*. mitogen). The authors concluded that collectively, these results suggest that exposure to 1 mA of current for two weeks had no significant effect on the immune function of dairy cattle.

Four groups of 8 cows each were divided into a control group (n=2) and Treatment groups (n=6) and monitored for a 14-day pre-treatment period followed by a 21-day treatment during which a single-cycle, 60-Hz transient current was applied to water bowls once every second, and a 14-day post treatment period (4, 17). Cows in these experiments were exposed to the transient current whenever they attempted to drink. Exposure levels were set relative to the sensitivity of individual animals to short duration exposure to take into account the wide range of sensitivities among cows. The exposure levels ranged from 4.9 to 7.8 mA rms for cows exposed at their behavioral reaction threshold (n=6), 6.0 to 9.5 mA rms for cows exposed to 1.1 mA rms above their behavioral reaction threshold (n=6), 6.4 to 12 mA rms for cows exposed to 2.2 mA above their behavioral reaction threshold and 7.8 to 14 mA rms (n=6) to cows exposed to 150% above their behavioral reaction threshold. Animals showed an acclimation to the transient current exposure with avoidance behaviors most prominent immediately after exposure and reduced avoidance response with increasing exposure time. Significant reductions in water and feed intake, and milk production were measured on the first three days of exposure for cows exposed to 150% of their reaction threshold current level. The current level required to elicit this short term reduction in water and feed intake and milk production was thus considerably higher than that to produce a behavioral response. Average changes in feed and water intake and milk production during the 21 day treatment period were not significant when compared with the 14-day pre-treatment period. No changes in somatic cell count or linear score were found. Three cows experienced an elevated SCC and were treated for mastitis during the experiment. Two of the cows affected by mastitis were the control cows and one incident of mastitis occurred during the Pre-treatment period for a cow that was later exposed to current at the behavioral response threshold. All three of the mastitis incidents were for cows in test stall number 3. This was cleaned and disinfected and the cow housed in that stall for the final block did not experience an elevated SCC. This study confirms results of previous studies and field observations noting rapid acclimation to voltages as well as changes in animal behaviors with no measurable decline in water or feed intake or milk production and no increase in SCC or incidence of mastitis.

The effects of permanent or random exposure to stray voltage applied to the water trough were evaluated on milk production and stress physiology of 74 Holstein cows (5) that were assigned during two 8-wk experimental periods to 1 of 3 treatments: permanent exposure (1.8 V, n = 23), random exposure of 36 hr/week, (1.8 V, n = 25), and no voltage (C, n = 26). Voltage was applied between metallic water bowls and a metallic plate on the floor. The average cow+contact resistance was measured as 516 Ohms and the current applied was 3.6 +/- 0.08 mA. The absence of differences between treatments for SCC was verified after the cows were assigned to their groups. On the first day of voltage exposure, permanently exposed cows had higher activity levels than control cows (9.8 vs. −2.3 periods of movement/hr). During the eighth week of exposure, randomly exposed cows had higher activity levels than control cows (4.2 vs. −7.7 periods of movement/hr). The randomly exposed cows had higher milk cortisol concentration (0.21 ng/mL) than the permanently exposed cows (0.14 ng/mL) during the eighth week of exposure, but neither group was different than the control group (0.15 ng/mL) and no difference in plasma cortisol concentration was observed between groups. There was a transient decrease in milk yield on the second day of exposure in permanently cows (−1.4 kg) and on the third day of exposure in randomly exposed cows (−3.5 kg) compared with control cows. No differences were observed between treatments for cortisol response after an ACTH challenge during the seventh week of exposure. No effects of voltage exposure were observed on daily water intake or SCC. The authors concluded that stray voltage exposure at these levels could be considered a mild chronic stressor in dairy cows, especially when it was unpredictable, with only slight modifications in stress physiology accompanied by changes in activity and no impairment of milk production or SCC.

Summary

If animal contact voltage reaches sufficient levels, animals coming into contact with grounded devices may receive a mild electric shock that can cause a behavioral response. At voltage levels that are just perceptible to the animal, behaviors indicative of perception (e.g., flinches) may result with little change in normal routines. At higher exposure levels, avoidance behaviors may result. The direct effect of animal contact with electrical current can range from:

- Mild behavioral reactions indicative of sensation, to
- Involuntary muscle contraction, or twitching, to
- Intense behavioral responses indicative of pain,

The indirect effects of these behaviors can vary considerably depending on the specifics of the contact location, level of current flow, body pathway, frequency of occurrence, and many other factors related to the daily activities of animals. There are several common situations of concern in animal environments:

- Animals avoiding certain exposure locations which may result in:
  - Reduced water intake if exposure is required for animals to access watering devices,
  - Reduced feed intake if exposure is required for animals to accesses feeding devices or locations.
- Difficulty of moving or handling animals in areas of Voltage/current exposure
- The physiological implications of the release of stress hormones produced by contact with painful stimuli

The severity of response will depend upon the amount of electrical current (measured in milliamps, mA) flowing through the animal's body, the pathway it takes through the body and the sensitivity of the individual animal. The results of the combined current dose response experiments, voltage exposure response experiments, and measurements of body and contact resistances is consistent with the lowest (worst case) cow + contact resistance as low as 500 Ohms as estimated by the authors of USDA handbook 696 (Lefcourt, 1991) that may occur in some unusual situations on farms (firm application of the muzzle to a wet metallic watering device and hoof contact on a clean, wet, contoured metallic plate on the floor). These studies on responses of dairy cows to electrical exposure agree well with each other and with predictions from neuro-electric theory and practice. There is a high degree of repeatability across studies in which exposures and responses have been appropriately quantified.

For confirmation, a potential of 2-4 volt (60 Hz, rms) must be measured between 2 points that an animal might contact (or animal contact measurement), and some animals should exhibit signs of avoidance behavior. The animal contact voltage measurement with an appropriate shunt resistor value provides the only reliable indication of exposure levels. Voltage readings at cow contact points should be made with a 500 or 1,000 Ohm resistor across the 2 measuring leads to the cow contact points in addition to open circuit measurements. Readings without the use of a shunt resistor are meaningless.

The only studies that have documented adverse effects of voltage and current on cows had both sufficient current applied to cause aversion and forced exposures (i.e., animals could not eat or drink without being exposed to voltage and current) and all of the indirect responses (reduced water or intake and milk production) were behaviorally mediated. It is typical for voltage levels to vary considerably at different locations on a farm. Decreased water and/or feed intake or undesired behaviors result only if current levels are sufficient to produce aversion at locations that are critical to daily animal activity, e.g., feeders, waterers, and milking areas. If an aversive current occurs only a few times per day, it is not likely to have an adverse effect on cow behavior. The more often an aversive voltage occurs in areas critical to cows' normal feeding, drinking, or resting, the more likely it is to affect cows.

A number of studies have been done to investigate potential detrimental physiological responses that may result from animals' exposure to voltage and current. The literature review presented in this paper summarizes 46 research trials on groups of cows exposed to know levels of voltage and/or current. Many these were part of the same experiment but exposed cows at different levels of voltage or current. None of these trials or experiments (some using aggressive exposure of cows to mastitis organisms) showed a significant effect of voltage/current exposure on SCC or the incidence of mastitis. Many of these studies showed behavioral modification and some showed minor changes in milk yield, milk composition or stress hormones (especially cortisol). These studies have shown that increased concentrations of the stress hormone cortisol do not occur at levels below behavioral response levels and only become apparent in some, but not all, cows at substantially higher voltage/current exposures than the threshold required for behavioral modification. This body of research indicates that while exposure to stray voltage at levels of 2 V to 4 V may be a mild stressor to dairy cows it does not contribute to increased SCC or incidence of mastitis, or reduced milk yield.

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Table 1. Summary of constant current exposures reported by exposure level. Some groups were part of the same experiment that used several different treatment levels. (n = the number of cows in the treatment group, RF = right front, RR = right rear, milk = milk yield, FCM = fat corrected milk, fat% = milk fat percentage, prot% = milk protein percentage, Rmilk = residual milk harvested after machine milking, feed = feed intake, water = water intake, L1 = 1st lactation cows, L2 = second or more lactation cows).

Ref	n	Exposure Level	Exposure Pathway	Exposure Pattern and Duration	Negative Response (no statistically significant change)	Non-significant trends noted	Significant Responses
39	12	1 mA	front - rear hooves	14 days 10 min on,10 min off	Cortisol, lymphocyte blastogenesis[a], immunoglobulin production, oxidative burst (Chemiluminescence PMA), standing and lying behavior,		Lymphocyte blastogenesis response to *Staph. aureus* mitogen
38	48	1 mA	front - rear hooves	During one milking	Milk, average milk flow rate, max milk flow rate, activity, strip yield		
21	8	1 mA to 5.3 mA	front - rear hooves	5 min exposures w/ ascending series of 4 levels	Cortisol (Note: significant cortisol increase observed during hoof trimming)		Some behaviors
14	7	2.5 mA	RR Hock-RF knee, EKG patch	10 s	Heart rate, prolactin, norepinephrine epinephrine and glucocorticoids		
28	7	3.6 mA	RR Hock-RF knee, EKG patch	7 days at milking (2x) 5s on, 25s off,	**Wisconsin Mastitis Test**, milk, milking duration		Behavior, +3 beats/min heart rate, +time to peak oxytocin, +peak milk flow, +peak prolactin, + prolactin curve
12	6	4 mA	Udder-Hooves	3 days, Intermittent 5 s bursts during milking (2x)	**SCC,** cortisol, prolactin, oxytocin, milk, fat%, prot%, Rmilk, peak milk flow, time to peak milk flow, milking duration,		Some behavior changes
12	6	4 mA	Sub-dermal electrodes	3 days, during morning milking	**SCC,** milk, fat%, prot%, feed, water	-1% milk	+heart rate, carotid arterial blood pressure, mammary blood flow, behaviors in first 30 s of exposure
27	8	4 mA	Sub-dermal electrodes	4 days, with 5 min of intermittent exposure (5s on, 5s off), 6 times/day	**SCC,** milk, fat%, prot%, feed, water	-1% milk	Some behavior changes with acclimation
29	6	4 mA	Udder-hooves	7 days, for 5 min before milking and during milking (2x), 5s on 25 s off	**SCC,** prolactin, oxytocin, cortisol, milk, prot%, fat%, milking duration, peak milk flow, duration of peak milk, Rmilk,	**-SCC,** +milk,	Some behavioral changes with acclimation

4	6	4.9 to 9.5 mA	metallic water bowl - hooves	21 days, 1 per s, while drinking, BRT[c]	**SCC,** milk, water, feed		
31	8	5 mA	teat cup electrodes – rear hooves	3 days, 6 milkings, L1 cows	**SCC,** milk, fat%, prot%, behavior	**+SCC,** -milk	-1 min. milking duration
13	6	5 mA	Udder-Hock EKG patch	20 min continuous, 2 milkings	Norepinephrine, prolactin, milk		+blood oxytocin, behaviors with acclimation
13	6	5 mA	Udder-Hock EKG patch	20 min intermittent (5s on 20s off) , 2 milkings	Norepinephrine		-milk yield, -prolactin, +oxytocin
14	7	5 mA	RR Hock-RF knee, EKG patch	10 s	Heart rate, prolactin, norepinephrine Epinephrine and glucocorticoids		
28	6	6 mA	Udder-Hock EKG patch	7 days at milking (2x) 5s on, 25s off,	**Wisconsin Mastitis Test,** milk, time to peak oxytocin, milking duration,		Behavior (one cow removed for severe behavior) +3 beats/min heart rate, +peak milk flow, +peak prolactin, +prolactin curve
4	6	6.0 to 9.5 mA	metallic water bowl - hooves	21 days, 1 per s, while drinking, BRT[c] +1 mA	**SCC,** milk, water, feed		
4	6	6.4 to 12 mA	metallic water bowl - hooves	21 days, 1 per s, while drinking, BRT[c] +2 mA	**SCC,** milk, water, feed		
14	7	7.5 mA	RR Hock-RF knee, EKG patch	10 s	Heart rate, prolactin, norepinephrine Epinephrine and glucocorticoids		
4	6	7.8 to 14 mA	metallic water bowl - hooves	21 days, 1 per s, while drinking, BRT[c] x 1.5	**SCC,** milk, water, feed on days 4-21 of exposure		-water, -feed, -milk; first three days of exposure
31	8	8 mA	teat cups electrodes – rear hooves	3 days, 6 milkings, 2L cows	**SCC,** milk, fat%, prot%, milking duration, behavior	**-SCC,** -milk	-cortisol 2 min. prior and 6 min. after milking began, similar at other times.
12	6	8 mA	Udder-Hooves	3 days, Intermittent 5 second bursts during milking (2x)	**SCC,** milk, fat%, prot%, Rmilk, peak milk flow, time to peak milk flow, milking duration	+prolactin, +oxytocin	Some behavior changes, +cortisol

29	6	8 mA	Udder-hooves	7 days, for 5 min before and during milking (2x), 5s on 25 s off	**SCC,** prolactin, oxytocin, cortisol, milk, prot%, fat%, milking duration, peak milk flow, duration of peak milk flow, Rmilk	**-SCC,** +milk, +cortisol, +milking duration	+cortisol, delayed oxytocin, Some behavioral changes with acclimation
14	7	10 mA	RR Hock-RF knee, EKG patch	10 s	Heart rate, prolactin, norepinephrine, glucocorticoids		+Heart rate immediately after shock, Epinephrine doubled in two exceptional cows
14	7	12.5 mA	RR Hock-RF knee, EKG patch	10 s	Heart rate, prolactin, norepinephrine epinephrine and glucocorticoids		+Heart rate immediately after shock

[a] response to mitogens, concanavalin A, phytohemagglutinin, pokeweed.
[b] IgG serum, IgG invitro, IgA serum, IL-1 serum, IL-1 in vitro, IL-2 serum, IL2-in vitro
[c] BRT = pre-determined behavioral reaction threshold

Table 2. Summary of constant voltage exposures reported by exposure level. Some groups were part of the same experiment that used several different treatment levels. (n = the number of cows in the treatment group, milk = milk yield, FCM = fat corrected milk, fat% = milk fat percentage, fatKG = kilograms of fat produced per day, prot% = milk protein percentage, protKG = kilograms of protein produced per day, lact% = milk lactose percentage, lactKG = kilograms of lactose produced per day, Rmilk = residual milk harvested after machine milking, feed = feed intake, water = water intake, L1 = 1st lactation cows, L2 = 2nd or more lactation cows).

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Ref	**n**	**Exposure Level**	**Exposure Pathway**	**Exposure Pattern and Duration**	**Negative Response (no statistically significant change)**	**Non-significant trends noted**	**Significant Responses**
30	6	0.5 V	metallic water bowl - rear hooves	21 Days, when drinking	**SCC**, c**linical mastitis, milk conductivity,** body temperature, reproduction		
30	6	1 V	metallic water bowl - rear hooves	21 Days, when drinking	**SCC, clinical mastitis, milk conductivity,** body temperature, reproduction		
33	10	1 V	metallic water bowl - rear hooves	Full lactation when drinking	**SCC, incidence of mastitis**, milk, fat%, prot%, feed, water, hoof problems, body weight, days to first breeding, days open, service per conception, calving interval, visible abortion, calves born dead		
36	4	1 V	metallic water bowl - rear hooves	7 days	**SCC, Staph. *aureus* infected quarters,** immune gamma-globulins[a], cortisol, blood chemistry[b], milk, fat%, prot%, water, feed	+0.7 ng/mL cortisol	
37	4	1 V	metallic water bowl - rear hooves	7 days *Strep. uberi*s challenge after milking (2x)	**SCC, *Strep. uberis* infected quarters,** milk, fat%, prot%, feed, water,		
34, 35	30	1 V	metallic water bowl - hooves	56 to 84 days, 0.3 V cont. w/ two 3-hr periods of 1 V	Treatment and carry-over effects: **SCC,** milk, FCM, fat KG, protKG, lactKG, prot%, feed, water, behavior, breeding, milking duration		Treatment: +0.12 fat%, +0.06 lactose% Carry-over: +0.2 lactose%
31	7	2 V	teat cups electrodes - rear hooves	During one milking	**SCC,** milk, fat%, prot%, Rmilk fat%, Rmilk prot%, behavior, milking duration	-fat%, -prot%, +Rmilk fat%, in 1L cows; +fat%, +prot%, -Rmilk fat%, +Rmilk prot% in 2L cows	

30	6	2 V	metallic water bowl - rear hooves	21 Days, when drinking	**SCC, clinical mastitis,** milk conductivity, body temperature, reproduction		
33	10	2 V	metallic water bowl - rear hooves	Full lactation, when drinking	**SCC, incidence of mastitis, milk,** fat%, prot%, feed, water, hoof problems, body weight, days to first breeding, days open, services per conception, calving interval, visible abortion, calves born dead		Delay to drink
36	4	2 V	metallic water bowl - rear hooves	7 days	**SCC, staph. *aureus* infected quarters,** immune gamma-globulins[a], cortisol, blood chemistry[b], milk, fat%, prot%, water, feed	+0.8 ng/mL Cortisol	Delay to drink
37	4	2 V	metallic water bowl - rear hooves	8 days w/ *Strep. uberis* challenge after milking (2x)	**SCC, *Strep. uberis* infected quarters,** milk, fat%, prot%, feed, water	+2% water intake	
34, 35	30	2.5 V	metallic water bowl - hooves	56 to 84 days, 0.75 V cont. w/ two 3-hr periods of 2.5 V	**SCC,** milk, FCM, fatKG, protKG, lactKG, fat%, prot%, lact%, feed, water, behavior, breeding (treatment and carry-over effects)		+12 s milking duration, carry-over effect +42 s milking duration
31	15	4 V (4.1 mA aver, 2 mA - 7 mA range)	teat cups electrodes - rear hooves,	During one milking	S**CC,** milk, fat%, Rmilk fat% milking duration	1L cows; -fat%, -prot%, +Rmilk fat% 2L cows +fat%	1L cows; Behavior changes. 2L cows; +0.1% prot%, +0.2% Rmilk prot%, -1.4 Rmilk fat%
30	6	4 V	metallic water bowl - rear hooves	21 Days, when drinking	**SCC, clinical mastitis,** milk conductivity, body temperature, reproduction		
33	10	4 V	metallic water bowl - rear hooves	Full lactation, when drinking	**SCC, incidence of mastitis, milk,** fat%, prot%, feed, water, hoof problems, body weight, days to first breeding, days open, services per conception, calving interval, visible abortion, calves born dead		Delay to drink, 1 cow & 1 heifer refused to drink for 36 hr, 1 place-holder heifer, no grain for 36 hr
36	4	4 V	metallic water bowl - rear hooves	7 days	**SCC, *staph. aureus* infected quarters,** immune gamma-globulins[a], cortisol, blood chemistry[b], milk, fat%, prot%, water, feed	+1.2 ng/mL cortisol	Delay to drink

37	4	4 V	metallic water bowl - rear hooves	9 days, *Strep. uberis* challenge after milking (2x)	**SCC, *Strep. uberis* infected quarters,** milk, fat%, prot%, feed, water	+3% water intake	
34, 35	30	5 V	metallic water bowl - hooves	56 to 84 days, 0.75 V cont. w/ two 3-hr periods of 5 V	SCC, milk, FCM, fat%, feed, milking duration, behavior, breeding. Treatment and carry-over effects except as noted		Treatment effect; -0.05 prot%, -8% water. Carry-over effects; -0.8 kg milk, +0.1 prot%, -1 kg FCM, -0.1 protKG, -0.2 lactKG
31	15	8 V (9.1 mA aver, 4-14 mA range)	teat cups electrodes - rear hooves,	During one milking,	SCC, milk, fat%, Rmilk fat%, Rmilk prot% in 1L cows, milking duration	1L cows;-fat%, -prot%, +Rmilk fat%. 2L cows; +fat%, +prot%, -Rmilk fat%	Behavior changes, 1 heifer kicked milking unit off; +0.1% Rmilk prot% in 2L cows
31	8	16 V	teat cups electrodes - rear hooves	During one milking	SCC, milk, fat%, prot%, Rmilk fat%, Rmilk prot%, milking duration	1L cows; -fat%, -prot%, +Rmilk fat%. 2L cows; +fat%, +prot%, -Rmilk fat%, +Rmilk prot%	Behavior changes, 2 cows kicked milking unit off

[a] IgG, IgA, IgM

[b] sodium, potassium, chloride, bicarbonate, anion gap, urea, creatinine, calcium, phosphate magnesium total protein, albumin, globulin, glucose, alkaline phosphatase, ast/PSP, SDH, hGGT, indirect, direct and total bilirubin, ck, iron, and TIBC

Figure 1. Summary of Behavioral Response thresholds for Dairy Cows exposed to ascending series of 60 Hz current exposures. Current is expressed in equivalent 60 Hz rms values. Note: 60 Hz rms current values correspond to 60 Hz rms voltage values for a typical value of 1000 Ohms for cow + contact resistance, e.g. 4 mA rms = 4 V rms. To obtain 60 Hz rms values for a worst case 500 Ohms cow + contact resistance divide 60 Hz rms current values by 2, e.g. 4 mA = 2 volts). (---- first behavioral response threshold for 365 cows, … discomfort or involuntary muscle contraction threshold for 133 cows, -.-.- aversion threshold for 36 cows)

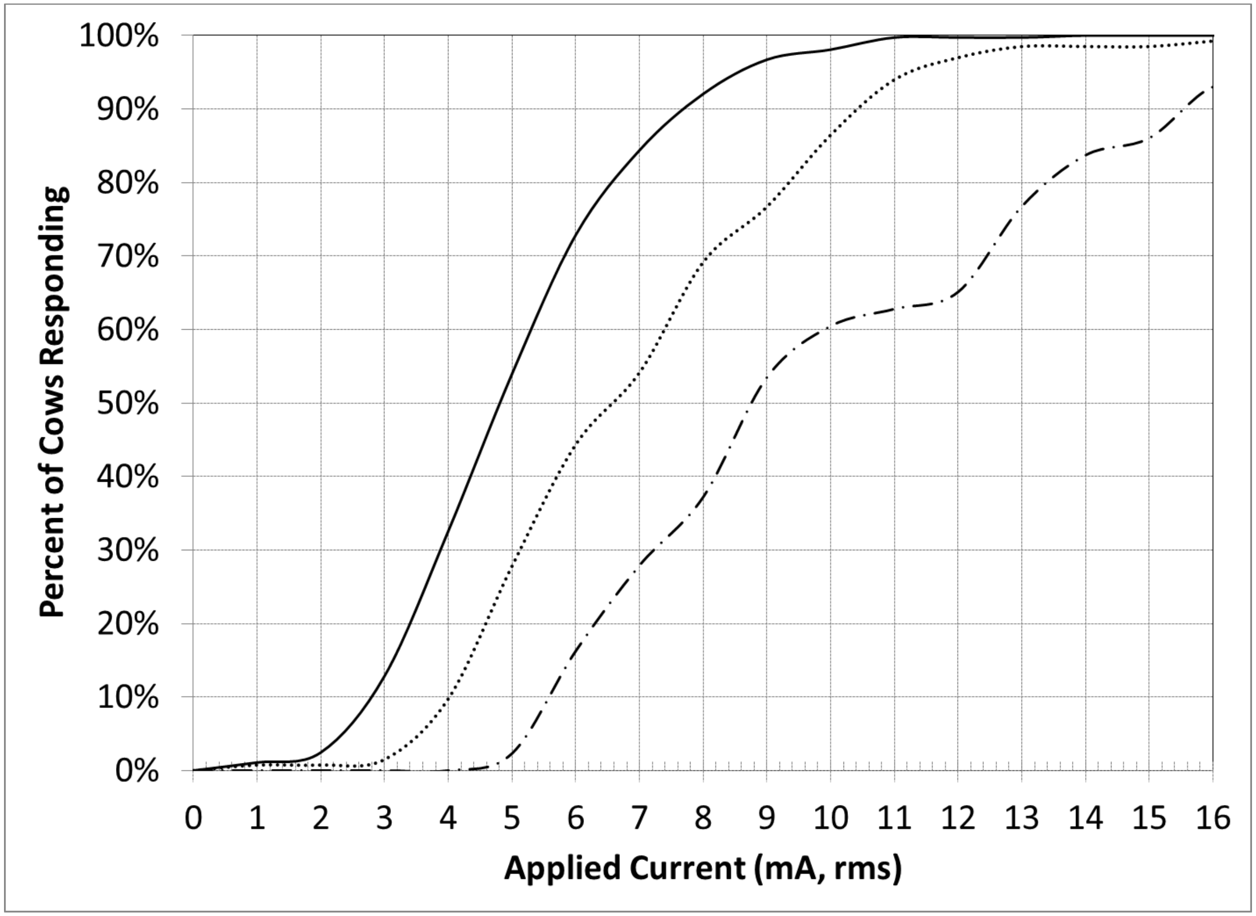

Figure 2. Summary of Behavioral Response thresholds for the 5% most sensitive Dairy Cows. Voltages are expressed in zero to peak rather than rms values for conveinience in reading an oscilloscope screen for monophasis and biphasic waveforms. The voltage levels assume a 500 Ohm cow + contact resistance. The phase duration is the time between zero-crossings foralternating waveforms. (---- multiple cycle sine wave, … monophasic sine, -.-.- biphasic sine wave).