

# DAIRY COW SENSITIVITY TO SHORT DURATION ELECTRICAL CURRENTS

D. J. Reinemann, L. E. Stetson, J. P. Reilly, N. K. Laughlin

**ABSTRACT.** *The results of 299 tests to determine the behavioral response threshold of dairy cows to a variety of short-duration or 'transient' electrical current waveforms via the muzzle to 4-hoof pathway are reported. The phase duration of stimuli tested ranged from 10  $\mu$ s to 8.3 ms. Phase duration is defined as the time between two consecutive zero crossing points of the waveform (e.g., 1/2 cycle of a sinusoidal waveform). The amplitude of the electrical currents, at a given phase duration, were increased in an ascending series. The lowest threshold current at which an observer could detect a behavioral change was determined for individual cows. Various behaviors were quantified. Facial activity was the most sensitive behavioral response followed by front hoof lifting. Human observers measurements of hoof lifting agreed well with automated recording of animal motion. Tail motion showed no statistically significant response to the current stimulus. Cows were less sensitive (e.g., more current was required to elicit a response) to shorter duration or higher frequency waveforms. The strength-duration relationship observed for cows agreed well with neuro-electrical models previously verified by human response.*

**Keywords.** *Stray voltage, Stray current, Transient voltage, Dairy cows, Electrical stimulation.*

Research conducted before 1991 on the effects of stray voltage on dairy cows and investigative methods are summarized in a U.S. Department of Agriculture stray voltage handbook (USDA, 1991). At the time that this handbook was published, most of the research on the effects of electrical phenomena on dairy cows had been confined to continuous 60 Hz voltages and current. Recommendations for further research cited in this handbook include studies of the variability in sensitivity and response to current for a large number of dairy animals and evaluation of short-term and long-term exposure to transient voltage and current on animals.

It has been known for some time that both cows and humans are less sensitive to short duration current pulses. Reports of experiments on human sensitivity to short duration current exposure can be found as early as 1901 (Weiss, 1901). Electric fences and cow trainers, use a short-duration current to control animal behavior, have been in use for decades. Electric fences typically operate with cow contact voltages of up to 10,000 V. This elevated voltage and current is required because of the decreased sensitivity to high frequency or short duration pulses. This voltage and the resulting current level has been chosen to

create an avoidance response in cattle but is not expected to cause harm to the animal.

In one study on the response of dairy cows to 60-Hz current, Brennan and Gustafson (1986) examined the sensitivity of dairy cows to 1, 3, 9, and 15 cycles of 5-mA, 60-Hz current. No statistically significant difference was found between these treatments. Currence et al. (1990) examined the sensitivity of 21 dairy cows exposed to 60-Hz rms currents with stimuli of 1, 10, and 100 cycles. The exposure pathway for these studies was from a single front hoof to a single rear hoof. Cows responded at a lower current for the 10 and 100 cycle stimuli than for single cycle stimuli.

Gustafson et al. (1988) reported on a study of dairy cow sensitivity to stimuli other than 60-Hz sine wave. The perception threshold for monophasic rectangular stimuli, ranging in duration from 0.52 to 265 ms was determined for six dairy cows. These studies showed that as the phase duration was decreased the current required to elicit a behavioral response increased. It was recommended that further study over expanded time and current ranges and with larger cow numbers was needed. A more recent study reported on an experiment conducted to determine the relationship between the frequency of multiple cycle waveforms and the current required to stop cows from drinking (Stringfellow et al., 1996; Aneshansley et al., 1997). The authors found that as the frequency of the waveform increased (shorter phase duration) the current required to stop cows from drinking increased.

Behavioral indicators have previously been used to evaluate sensitivity of dairy cattle to electrical phenomena. Henke et al. (1982) reported that behavioral response was as sensitive, or more sensitive, an indicator of perception than analysis of stress-related hormones in blood. The types of behavioral responses observed included muscle contraction and jumping or kicking. In a study by Norell et al. (1983) behaviors altered by current exposure included

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Article has been reviewed and approved for publication by the Information & Electrical Technologies Division of ASAE. Presented as ASAE Paper No. 96-3087.

The authors are **Douglas J. Reinemann**, Ph.D., *ASAE Member Engineer*, Associate Professor, University of Wisconsin-Madison, Department of Biological Systems Engineering, Madison, Wis.; **LaVerne E. Stetson**, *ASAE Fellow Engineer*, Agricultural Engineer, USDA-ARS, University of Nebraska, Lincoln, Nebr.; **J. Patrick Reilly**, Johns Hopkins University, Applied Physics Laboratory, Laurel, Md.; **Nellie K. Laughlin**, Ph.D., Associate Scientist, University of Wisconsin, Harlow Center for Biological Psychology, Madison, Wis. **Corresponding author:** Douglas J. Reinemann, University of Wisconsin, 460 Henry Mall, Madison, WI 53706; voice: (608) 262-0223; fax: (608) 262-1228; e-mail: djreinem@facstaff.wisc.edu.

hoof movement and suppression of a learned response, (pressing a plate with the muzzle to receive grain). No suppression of this response was noted at 6 mA for front-rear hoof exposure, although increased hoof movement was noted. The current required to suppress a grain reward response were initially between 1- to 2-mA rms for four cows with higher levels required in later sessions. The other two cows had a suppression threshold of 4.5-mA rms. The authors state that a definitive lower limit for a suppression threshold could not be derived from these data. Gustafson et al. (1985) reported on a study in which 0.5-s pulses of 60-Hz current were applied from front to rear hooves, mouth to all hooves and body to all hooves. Cows were trained to lift their hooves to terminate the current exposure. Responses to the 60-Hz current became significant at the 3-mA level for the front-rear hoof pathway and mouth to all hooves pathway. Responses became significant between 4.5 and 6 mA for the body to all hooves pathway. Other behaviors, such as muscle contraction, startled jerks, and shoulder shakes, were noted. These other behaviors appeared to be idiosyncratic to certain animals and were only reported for the body to all hooves pathway.

Mouth opening, escape behavior, hoof lifting, and sudden muscle movement were used to measure the reaction to varying duration monophasic stimuli applied through a bit in the cows' mouth in a study reported by Gustafson et al. (1988). Currence et al. (1990) cited sudden muscle contraction, hoof lifting and humping of the back as visible indicators of response to single front hoof to single rear hoof current stimuli. These visual observations were considered by the investigators as a more repeatable indicator of animal response than heart rate, blood pressure, or electrically sensed muscle reactions.

A behavioral indicator cited by Aneshansley et al. (1992) was lifting hooves when continuous 60-Hz current was applied to the milking unit during milking. The increase became significant when the voltage exceeded 4 V (corresponding to 2 to 7 mA of current) for heifers and 8 V (corresponding to 4 to 14 mA of current) for cows. No change in milk production, milk quality or cortisol level was found. Lefcourt et al. (1985) conducted a study in which 3- and 6-mA rms current was applied through EKG electrodes attached to a shaved area on the rear and front legs immediately before milking. The authors concluded that behavioral responses appeared more sensitive to current exposure than hormone concentrations or milking characteristics.

A comprehensive review of the biophysical aspects of electrical stimulation has been published (Reilly, 1992) as well as a review of the specific factors affecting dairy cow sensitivity (Reilly, 1994). Both sensation and muscle reactions can be elicited with electric currents conducted through the skin. These effects occur when sensory or motor neurons are excited by a voltage potential across the membrane of a nerve cell. The minimum potential required to excite the nerve cell is known as the action potential. It appears from the many studies conducted on dairy cows that behavior is the most sensitive response to electrical stimuli. These behaviors are most probably associated with sensory nerve excitation.

Several models have been developed to describe the relationship between the duration and magnitude of a

current pulse needed to produce sensation. A nonlinear model of myelinated, A-nerve fibers consisting of capacitive, resistive, and potential source elements was developed by Reilly (1992). Myelinated nerve fibers were chosen because of their lower stimulation thresholds compared with other nerve types.

Neurological models and experimental data from human subjects indicate that the efficacy of an electrical stimulus depends critically on its waveform (Reilly, 1992, 1994). An example of the effect of phase duration and waveform, derived from a myelinated nerve model, in which a 20- $\mu$ m nerve fiber is excited by current from a small electrode within the biological medium, is shown in figure 1. The horizontal axis is the phase duration of the current stimulus, i.e., the duration of the monophasic pulse, or the duration of one phase of the biphasic pulses. The right-hand vertical axis is the peak current magnitude (threshold current) needed to excite the nerve; the left-hand axis is the phase charge, i.e., the amount of charge in the monophasic current, or in one phase of the biphasic currents. The curve for monophasic stimuli shown in figure 1 is often called a strength-duration (SD) curve. The form of the strength-duration relationship for monophasic, pulsed stimuli derived from the myelinated nerve model compare well with an empirical model attributed to Weiss (1901):

$$I_T = I_0 \left( 1 + \frac{\tau_c}{t} \right) \quad (1)$$

where

$I_T$  = threshold current for nerve excitation (mA)

$I_0$  = minimum threshold current for an infinitely long pulse or Rheobase (mA)

$t$  = duration of monophasic pulse ( $\mu$ s)

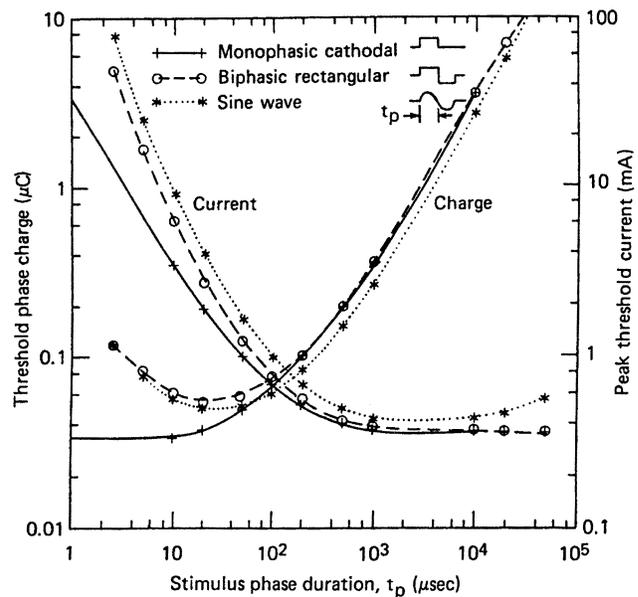


Figure 1—Strength-duration relationships derived from the myelinated nerve model: current thresholds and charge thresholds for single-pulse monophasic and for single-cycle biphasic stimuli with initial cathodal phase, point electrode 2 mm distant from 20- $\mu$ m fiber. Threshold current ( $t_p$ ) refers to the peak of the stimulus waveform. Charge refers to a single phase for biphasic stimuli (from Reilly, 1992).

$\tau_e$  = strength-duration time constant related to the time response of tissue being excited ( $\mu\text{s}$ )

An interpretation of this relationship is that, for long duration monophasic stimuli, the threshold of excitation converges to a minimum current value referred to as the rheobase ( $I_0$ ). For short duration stimuli, the threshold of excitation converges to a minimum charge value. At short phase duration, the neurological response is based on the amount of electrical charge released into the nerve and is therefore affected by the waveform and its charge balance (area under positive and negative portion of current waveform). Note that for a rectangular monophasic pulse, the charge delivered is simply the product of the phase duration and the peak current.

The myelinated nerve models, as well as previous experimental data, suggest that the rheobase should be reached for a phase duration of about 120  $\mu\text{s}$  or longer for typical conditions of excitation. Likewise the minimum charge should be reached at a phase duration of 10  $\mu\text{s}$  or shorter (Reilly, 1992). The experimental strength-duration time constant may thus be determined by evaluating the stimulus threshold at two phase durations, one very long, and one very short.

Neurological models also suggest that at frequencies below 1000 Hz, there is little difference in the threshold current between single cycle and continuously applied sine waves. As frequency increases above this value, a continuous sine wave is predicted to have a lower threshold current than a single-cycle sine wave of the same frequency. Figure 2 illustrates this relationship in a strength-frequency (SF) curve, which represents the peak sinusoidal current threshold for neural excitation versus the frequency of a sinusoidal stimulus (Reilly, 1992, 1994). The two solid curves in figure 2 were derived from the myelinated nerve model. The theoretical foundation for

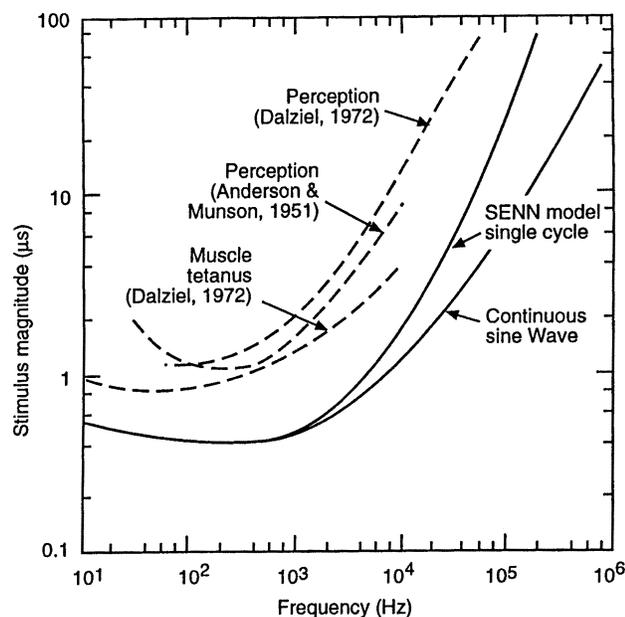


Figure 2—Strength-frequency curves for sinusoidal current stimuli. Dashed curves are from experimental data. Solid curves apply to myelinated nerve model. Experimental curves have been shifted vertically to facilitate comparisons (from Reilly 1992, 1994).

determining strength-duration and strength-frequency response curves is thus well developed. The form of these theoretical models has been found to correspond well to responses of humans.

The objectives of this study were to determine:

1. The sensitivity of dairy cows to a wide frequency range of transient currents.
2. Variability within the population of dairy cows to transient currents.
3. Adequacy of previously developed models in describing strength-duration and frequency-duration relationships for dairy cows.

## MATERIALS AND METHODS

Test stalls were constructed to allow precise control and measurement of electrical stimuli to individual cows and to eliminate interference from other electrical stimuli occurring in the cow environment. Cows were secured with head-locking stanchions supported on a wooden framework. The test stalls were similar to those normally used by the cows and were placed in the same barn in which the experimental cows were housed. The floor of the test stalls consisted of a wooden framework filled with two concrete pads (fig. 3). A 15-cm  $\times$  15-cm (6-in.  $\times$  6-in.) welded grid of 9.5-mm (3/8-in.) reinforcing steel was embedded in each pad. When a cow stood in the stall, the front hooves were on the front concrete pad and the rear hooves on the rear pad. The front and rear pads were bonded in all of the tests reported in this article. A copper plate was bolted to the surface of the rear pad to monitor the potential between the muzzle and rear hoof contact points.

The stalls were suspended off the barn floor by two load cells (Himmelstein & Co., Model SNC 11,000) attached between the back corners of the wooden stall frame and the wooden stall dividers. The fronts of the test stalls were supported by a single 73-mm diameter PVC pipe section 50 mm high, located at the center of the stall front. This arrangement provided for electrical isolation of the stall from all grounding paths. Signals from the load cells were read and processed by computer-based data acquisition systems for some trials. The load cells were used to provide a measure of cow motion in the following manner. The location of the center of gravity of the cow/stall system was calculated from the weight on each load cell every 0.001 s. The derivative of the change in location of the

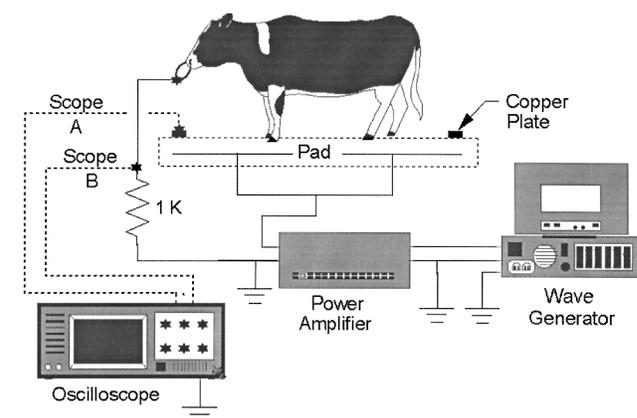


Figure 3—Test apparatus.

**Table 1. Current response threshold summary**

Experiment	A	B	C	D	E	F	G	H	I	J	K	L	M
Phase duration, $t_p$ (s)	8333	8333	8333	8333	1000	83	83	83	10	10	10	10	10
Frequency (Hz)	60	60	60	60	500	6k	6k	6k	50k	50k	50k	50k	50k
Number of cycles	1	1	5	9	1	1	9	100	1	1	1	5	833
Waveform*	NS,B Sine	S,B, Sine	B, Sine	M, Square	M, Sine	B, Sine	B, Sine	B, Sine					
Number of animals	24	96	24	24	24	24	23	12	12	8	8	8	12
Mean threshold (Peak mA)	7.8	10	7.1	7.6	14	71	58	36	182	543	1308	695	186
Standard deviation	2.5	3.0	1.5	2.6	4.9	15	19	5.8	37	42	164	85	38
Min threshold (Peak mA)	2.8	5.1	4.4	2	6.3	41	30	28	129	480	1000	600	124
Max threshold (Peak mA)	12.	19	10.5	13	27	103	103	48	257	600	1500	820	246

\* Waveform Codes: S = Symmetric, NS = Non-symmetric, B = Biphasic, M = Monophasic, Sine = Sinusoidal wave, Square = Square wave.

center of gravity with time was calculated ( $dx/dt$ ) for each time interval. A peak find routine was then used to count the number of times the value of the derivative exceeded a set value during the observation period. The derivative threshold was chosen to approximately correspond to a weight shift associated with a cow lifting its hoof and changing position in the stall.

Before each test the concrete surface of the test stalls were cleared of all bedding and thoroughly wetted with a salt solution. The surface was chosen to represent the lowest possible contact resistance encountered in the field. A computer based analog output board (Kiethly DAS 20) generated the waveform of the electrical stimuli to be applied (experiments A, C, E, H, and I in table 1). These signals were then converted to the appropriate current and voltage levels with a power amplifier (AB International, model 600Lx). Current was applied from the muzzle (using a non-piercing, ball-end nose clip) to all hooves pathway. A direct measurement of the current flowing through the cow was made during all tests using a digital storage oscilloscope to measure the voltage across a 1000- $\Omega$  resistor (5% precision, actual value 1003  $\Omega$ ) in series with the cow (channel A). The second oscilloscope channel measured the voltage across the copper plate mounted on the pad and the grounded side of the circuit. The difference between these two voltages (Channel A – Channel B) was taken as the cow-contact voltage.

The electrical apparatus was modified for a second series of experiments (B, D, F, G, J, K, and L in table 1). These modifications were made so that the apparatus could be run continuously for up to three weeks for aversion studies and to provide better control of the shape of the waveforms generated. A frequency generator was used to develop a constant frequency signal with sinusoidal waveform. This signal was then fed through a zero-crossing switching device which would block a pre-set number of pulses and then allow another pre-set number of cycles to pass. This signal was fed into the power amplifier used previously. The source voltage was held constant and a source resistance in series with the 1000- $\Omega$  resistor was varied to control the current delivered to the cow.

### TEST PROCEDURES

Holstein cows were selected for each experiment from the available pool of lactating cows from the research herd maintained at the University of Wisconsin's Arlington Agricultural Research Station. For the first series of experiments, cows were placed, one each, in each of four test stalls on the first day of testing. Non-piercing, ball-end nose clips were inserted in the cow's nose, access to food and water was established, and a minimum period of

60 min was allowed for cow adjustment to the stall and nose clip. Indications of the cow's adjustment to the new environment included consumption of feed, rumination, lying down, and drinking from water cups.

After cows were adjusted to their environment, a wire test lead was attached to the nose clip. A period of adjustment to this new stimulus was again allowed (5-10 min). Signs of adjustment to this stimulus include indications mentioned previously as well as no attempt to remove the nose clip or wire lead. The cows remained in the test stalls with the nose clips attached for three days and were tested once each day at approximately the same time of day.

Water and feed were withdrawn immediately before the testing period to prevent any electrical or behavioral interference. Cows were tested one at a time. Two trained observers, one in front of the cow and one behind, recorded animal behavior and movements during tests. The front observer recorded front hoof lifting (one event for each time a hoof was lifted from the pad) and any type of facial reaction including a twitch of the nose or ears or blink of the eyes. The rear observer recorded the number of rear hoof lifts and tail switches. Observers were trained with two people observing and recording the same response indicators during the same test. The observers independently observed and recorded responses. Paired observations were repeated until correlation of observed responses was in excess of 90% for several consecutive tests. Data from observers in-training were not used for analysis.

Tests consisted of repeated trials, each divided into two periods during which observations of cow movements were recorded. Each observer held a clipboard fitted with manually actuated counters. No electrical stimulus was applied during the first 30 s of each trial. The observers recorded the number of behavioral events on the manually actuated counters. In the second 30-s period of the trial, the cow was exposed to the electrical stimulus. The observers again recorded the frequency of behavioral events on another set of counters. The beginning and end of each observation interval were signaled to the observers through headphones. The observers were thus aware that the stimulus was applied but the signals were not audible to the cows. Tests were repeated on each cow with stimulus level increasing by about 15% of the previous value. At the completion of each test, each observer indicated the cows response recorded as negative (no change in behavior), marginal (possible change in behavior), or clear positive response (definite change in behavior). Current levels were increased until either observer noted a clear positive response. Test stimuli were then reduced in reverse order of the ascending series until both observers noted a negative

response. This completed the testing on that cow on that day. Each cow was tested in this manner for three consecutive days.

In the first experiment, a five-cycle, 60-Hz stimulus was applied once at the beginning of the 30-s observation period. In subsequent trials, the stimuli were applied once every 2 s over the 30-s observation period. This method of repeated stimuli produced a more noticeable response as it resulted in repeated behavioral responses during the stimulus period as described below.

The observation technique was modified for the remaining experiments (B, D, F, G, H, I, J, K, and M in table 1). The second series used only one observer who recorded whether the cow responded based primarily on observation of facial twitches and front hoof lifting. Statistical analysis of the behaviors from the first experiment showed that the most sensitive measures of cow response were facial twitches and front hoof motion as described below. Transient currents were applied to cows in an ascending series with steps of about 1 mA for 60-Hz stimuli, 10 mA for 6000-Hz stimuli, and 100 mA for 50,000-Hz stimuli. The stimulus was applied once per second over the 30-s observation period. Each cow was tested for two consecutive days and a third day if the results of the first two tests differed by more than two stimulus increments. The lowest current threshold for two tests within this agreement was used as the response threshold, measured as the peak current of the stimulus waveform.

#### STATISTICAL ANALYSIS OF BEHAVIORAL MEASURES

The behavioral response data from the first three experiments (A, C, and E) were analyzed using the SAS Generalized Linear Model (GLM) procedure for an analysis of variance. The objective of this analysis was to determine which behavioral measures corresponded to the observer's indication that the cow had responded to the stimulus. Two types of GLM analysis were performed. The first type used a 10-level model with class variables of Cow ( $n = 24$ ), Day ( $n = 3$ ), Response level ( $n = 4$ ), Treatment ( $n = 2$ ), and six interaction terms to predict the number of behavioral events during either the 30-s pre-stimulus or stimulus periods. The first factor is a between-subject variable and the last three are within-subject variables. Another GLM analysis was done using a six-level model with class variables of Cow ( $n = 24$ ), Day ( $n = 3$ ), Response level ( $n = 4$ ), and three interaction terms to predict the difference in behavioral events between the stimulus and pre-stimulus periods.

Both of these GLM analyses used data from four tests for each daily cow exposure. The data were from the two ascending current tests immediately below the observer-defined response level (R-- and R-), the response level (R) and the descending current test immediately following the response level (R-). The response level (R) was defined as the current level at which the observers first indicated a positive response to the stimulus. The two levels of the Treatment variable were the 30-s pre-stimulus observation period and the 30-s stimulus observation period. Further analysis of the significant response variables identified in the GLM analysis was done using univariate analysis to calculate the mean and confidence interval of the difference

in each behavior measure (activity during stimulus — activity during pre-stimulus periods).

## RESULTS AND DISCUSSION

### BEHAVIORAL RESPONSE MEASURES

The human observers' recording of hoof lifting were compared to computer motion sensor records using linear regression. The totals of front and rear hoof lifts were regressed against the computer motion counts. In some cases, the computer motion counter recorded more motions than the human observers recorded hoof lifts. This could occur if a cow shifted her center of gravity without lifting a hoof (e.g., a rocking motion). The computer counter could, conversely, record fewer events than the human observer if the cow lifted a hoof without a significant shift in her center of gravity (e.g., a pawing motion). Regressions of the number of hoof lifts recorded by human observers and weight shifts recorded by the computer motion counts for three experiments yielded correlation coefficients ( $R^2$ ) ranging from 0.74 to 0.80 with the slope terms ranging from 0.70 to 0.88. The overall agreement between the computer motion counter and human observers was quite good.

Results of the 10-level GLM analysis showed a significant cow effect ( $p < 0.05$ ) for all behavioral measures and all experiments. A significant ( $p < 0.05$ ) day effect was found for some response measures (tail motion for all experiments, face motion for experiments A and E, and front leg lifts for experiments C and E). This indicates that cows differed from each other and that on some days the group of cows was more active than on other days.

Results of the six-level GLM analysis showed a significant treatment effect ( $p < 0.05$ ) for the difference in face counts for all experiments. Only one stimulus was applied for the first experiment (A). Univariate analysis confirmed the results of the GLM analysis indicating a significant increase in face counts at the R-level, with no significant increase in observer monitored hoof lifts or computer monitored weight shifts. While the univariate test was significant, the mean increase in face counts was less than one event (0.66) in the 30-s observation period. Subsequent experiments used 15 stimuli applied once every 2 s in an attempt to increase the magnitude of all response variables.

A statistically significant increase ( $p < 0.05$ ) level was found for face counts, front hoof lifts and weight shifts at the response level (R) in the second two experiments (C and E). The increase in rear hoof lifts was also significant at the response level (R) in experiment E. Examples of the univariate analysis results for experiment E are shown in figure 4. The mean increase in face counts was statistically significant ( $p < 0.05$ ) for the R-levels for experiments C and E, however, the mean response was small ( $< 2.6$  events) and the distribution of responses was not normal with the majority of differences recorded as zero. It is likely that some animals exhibited subtle facial response on some days at the stimulus level immediately below the R-level.

The response levels reported in table 1 are the lowest response level of the three consecutive test days for each cow. This was considered as a conservative estimate of the level at which the stimulus is perceptible and perhaps mildly annoying, but not painful. The agreement between

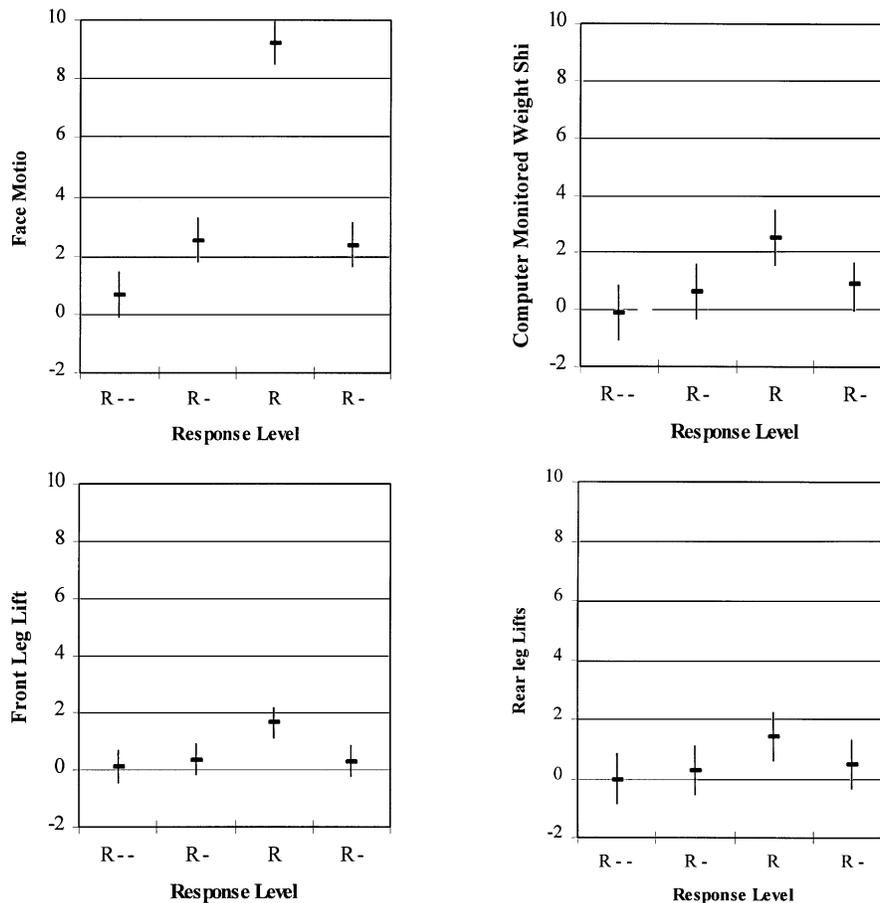


Figure 4—Univariate analysis of significant behavioral response variables.

the measurements made by human observers corresponded well with the unbiased measure made with the computer motion counter. The types of response behaviors documented agreed well with those reported by other researchers. All subsequent experiments (other than A, C, and E) relied on a single observer to determine whether the animal had responded to the stimuli base primarily on repetitive facial response and secondarily on front hoof lifting.

#### CURRENT THRESHOLDS

The mean, maximum and minimum response levels for each experiment are given in table 1. These results are presented as the peak current of the stimulus waveform. Steady 60-Hz voltage and current is generally reported as the rms average of the waveform. The rms values of short duration pulses are difficult to specify because of the highly damped and non-symmetric nature of the transient currents found on dairy farms (Dasho, 1994; Stringfellow et al., 1996). If biphasic waves are not symmetric about the zero axes, the ratio of the rms to peak value will be different than for the symmetric sinusoids usually encountered in steady 60-Hz stray voltages. Preliminary results from the first series of experiments were reported in rms average current (Reinemann et al., 1995). The rms average was determined from a digital recording of the applied stimulus. The single-cycle 60-Hz waveform used in experiment C was slightly non-

symmetric resulting in a ratio of rms to peak current of about 0.5, which is less than the value for a symmetric sine wave. Neurological models suggest that the phase duration, peak current, and shape of the waveform influence sensitivity. The peak current is a convenient number to measure with electronic recording equipment such as an oscilloscope. Peak current, phase duration and waveform are therefore reported in this article.

#### STRENGTH-DURATION SENSITIVITY

Response thresholds for **single cycle** stimuli are reported for experiments A, B, E, F, I, J, and K in table 1 and shown in figure 5. The single-cycle waveforms tested included **biphasic** sinusoidal waves with phase duration of 8333, 1000, and 83  $\mu$ s, and **biphasic sinusoidal**, **monophasic sinusoidal**, and **monophasic square** waves with phase duration of 10  $\mu$ s. The average, maximum, and minimum response levels from each sample group are plotted in figure 5.

The average response levels agree well with previous results reported by Gustafson and Brennan (1988) for 0.5- to 100-ms monophasic pulses. The strength-duration curve for the average response levels for biphasic sinusoidal stimuli follow the form of the myelinated nerve model (Reilly, 1992, 1994). However, the time scale of the experimental curve had a longer strength duration time constant as compared with the theoretical model. Such a temporal shift is also observed in human electro-cutaneous

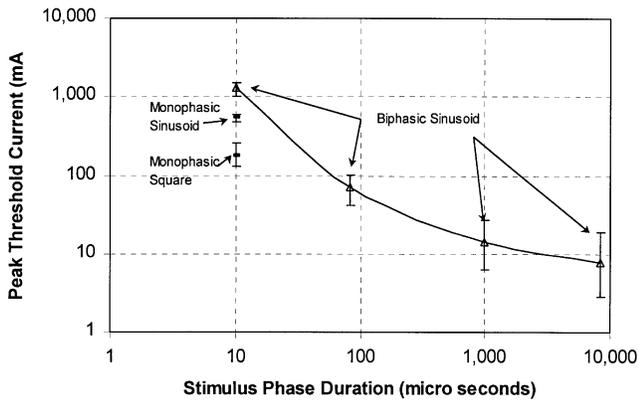


Figure 5—Strength-duration behavioral threshold current data for single cycle stimuli. The minimum, average, and maximum behavioral threshold current for each sample group are plotted.

sensitivity data. Previous results suggest that the horizontal time scale in the experimental plots may need to be scaled by a factor of about 2 for comparison with the theoretical model. As predicted by the myelinated nerve model, the threshold current for biphasic pulse is higher than for a monophasic pulse. Likewise the mean threshold current for a monophasic, sinusoidal pulse was greater than for a monophasic square wave.

For short duration stimuli, threshold charge, rather than peak current is the major factor affecting sensitivity. For biphasic stimuli, however, the curve relating threshold phase charge and phase duration is not monotonic, i.e., the minimum phase charge is attained at a particular value of phase duration. The results of these studies for the relative sensitivity for a biphasic sine wave, monophasic square wave and monophasic square wave follow the form predicted by the myelinated nerve model.

#### STRENGTH-FREQUENCY SENSITIVITY

Response levels for multiple cycle sine wave are given in table 1 and compared with single cycle sinusoidal stimuli in figure 6. The response level was lower for the multiple cycle events than for single cycle events at all frequencies. The response levels for multiple cycle stimuli agree well with those reported by Aneshansley et al. (1997) for multiple cycle stimuli ranging from 60 to 30,000 Hz. The difference between sensitivity to single cycle, biphasic sinusoids and multiple cycle sinusoids increased as the frequency of the waveform increased as predicted by the SENN model (Reilly 1992, 1994).

#### 60-Hz SENSITIVITY DISTRIBUTION

A cumulative frequency distribution of response levels for single-cycle 60-Hz stimulus for 120 cows from experiments A and B is shown in figure 7. Both of these experiments used a single cycle 60-Hz stimulus applied multiple times during the observation period. The mean and median response levels for experiment A were 23% and 15% lower than for experiment B. This difference could be due to several factors. The waveform used in Experiment A was not symmetric about zero while the waveform used in experiment B was symmetric. A single observer used repeated facial twitches as the primary indicator of response in experiment B, while two observers

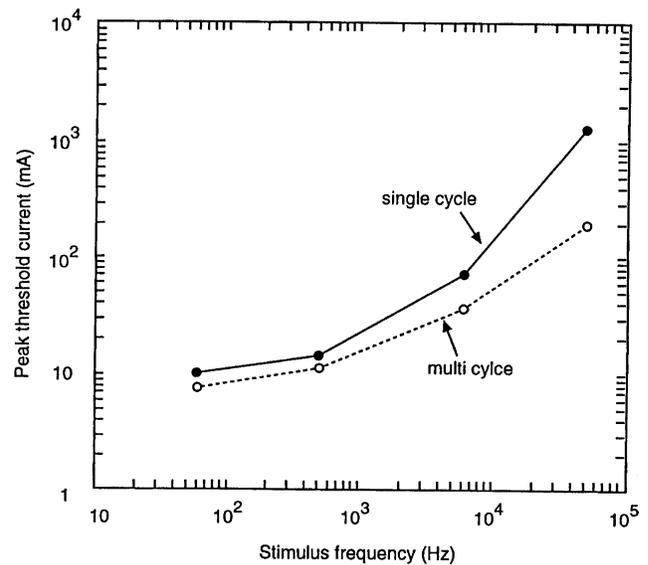


Figure 6—Strength-frequency threshold current data for single- and multiple-cycle sinusoidal stimuli. Threshold current refers to the peak of the stimulus waveform at which an animal response was recorded. Data are for the mean response threshold for the sample group.

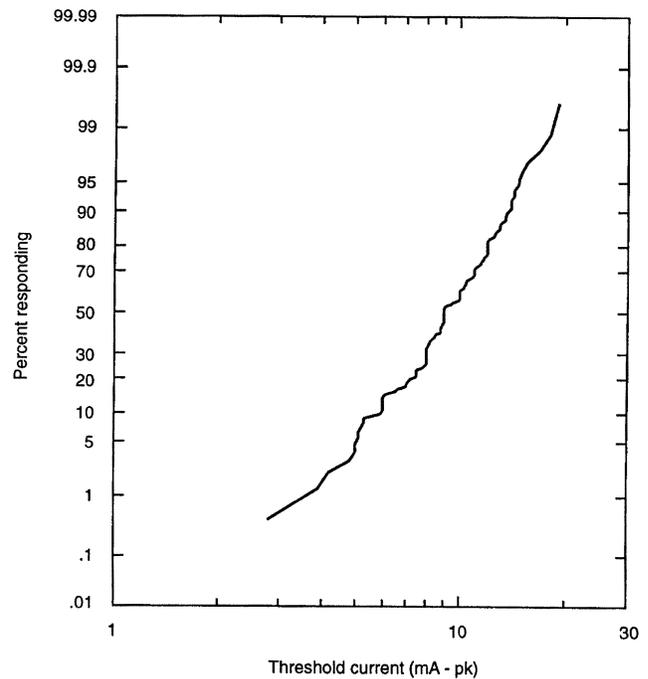


Figure 7—Cumulative frequency distribution for reaction threshold of 120 dairy cows for single-cycle, 60-Hz transient current. Threshold current refers to the peak current of the stimulus waveform at which an animal responded.

monitored two behaviors each in experiment A. The response levels reported for experiment A are the lowest of three consecutive test days, while the response levels for experiment B are the lowest of two tests within agreement of two stimulus level increments.

A lognormal distribution would appear as a straight line on figure 7. The data conform well to the log-normal distribution between the 5 and 99 percentile ranks. It would require a large sample to determine whether conformance

to this statistical model exists over a wider percentile range. The range in cow thresholds from the 90 to 10 percentile ranks encompasses a ratio of 2.4. Similar results have been obtained in tests of human perception of transient current, for which a log-normal model also applies, with the ratio for 90 to 10 percentile threshold encompassing a ratio of 2.0 for stimulation of the fingertip and 3.4 for stimulation of the forearm (Reilly, 1992).

In comparing these results with other published data for dairy cows, note that figure 7 represents peak current for transient stimulation; whereas, most other researchers report rms values for continuous 60-Hz current. The median reaction threshold in figure 7 is 9.0-mA peak. Adjusting that value to an rms metric (a multiplier of 0.707) and further adjusting from a single cycle to continuous stimulation (multiplier of 0.75), would infer a median threshold of 4.8 mA, rms for continuous 60-Hz stimulation. The median response levels reported by Currence et al. (1990) are 13% and 22% lower for single and multiple cycle to 60-Hz sinusoidal pulses, respectively, than those reported here adjusted for rms values. Several factors could account for this difference. The exposure pathway was different. The stimuli used by Currence et al. (1990) was applied from one front hoof to one rear hoof, which would increase the current density per hoof by a factor of three to four as compared to these experiments. This could reduce the sensitivity level to the total applied current. The single-cycle stimuli used by Currence et al. (1990) were not symmetric and had a very similar waveform as those used in experiment A reported here. Although the neurological models do not predict it, a charge balance effect as occurs for high frequency pulses may be present to a lesser degree for 60-Hz stimuli.

## SUMMARY AND CONCLUSIONS

The behavioral reaction threshold of dairy cows was determined for transient voltages ranging in phase duration from 8333 to 10  $\mu$ s (frequency from 60 to 50,000 Hz) and for single and multiple cycle stimuli. For the muzzle-to-hoof pathway tested here, increased facial activity appeared to be the most sensitive and repeatable behavioral indicator of response. Increased hoof activity (hoof lifting) recorded by human observers and cow motion measured with a computer base monitoring system were also significant indicators of response for the tests in which multiple stimuli were applied. The unbiased measure of cow motion as recorded by the computerized motion sensor was highly correlated with human observers recording of hoof lifting. No significant change in tail activity was observed in response to applied current.

The strength-duration relationship for dairy cow response to transient voltage pulses follows the form of previously developed neurological models. Sensitivity was affected primarily by phase duration with secondary effects of waveform. As the phase duration of the waveform was decreased, increased current was required to elicit animal response. Cows responded at lower threshold current for multiple as compared with single cycle stimuli of the same phase duration.

**ACKNOWLEDGMENTS.** The authors would like to acknowledge the significant contributions and suggestions for experimental design and interpretation of data from a variety of sources including, Dr. Eric Nordheim, Director of the UW CALS statistical consulting service, WDATCP/PSCW Stray Voltage program members, and the WDATCP Stray Voltage Advisory Board.

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