Unavoidable gridshock without scrambling circuitry from a faradic source of low-radio-frequency current*

DON R. JUSTESEN

Veterans Administration Hospital, Kansas City, Missouri 64128

NANCY W. KING

University of Kansas Medical Center, Kansas City, Kansas 66103

and

REX L. CLARKE

University of Kansas, Lawrence, Kansas 66044

A high-voltage radio-frequency stimulator was used as a source of motivational footshock in studies of conditional suppression. The circuit of the stimulator is presented schematically, then discussed in terms of affect induced by, gross behavioral response to, and electrical characteristics of, the stimulus. Near daily use of the stimulator across 6 months of formal assessment revealed that nonscrambled presentations of footshock via a grid of aluminum bars invariably resulted in stimulation of rat Ss and generated highly efficient conditional suppression of operant responding. While the stimulator was primarily designed to permit unconfounded presentation of gridshock in a 2,450-MHz microwave field, its simplicity and reliability suggest application in other situations requiring motivational shock.

In a previous report from our laboratories (King, Justesen, & Simpson, 1970), an operant conditioning system was described that is completely fabricated from low-loss dielectrical materials, a requirement imposed because the operant chamber is located in the exposure cavity of a microwave generator. In this work, the need for radiotransparency of materials housing an experimental S was one consideration; the other was that metallic operanda and reinforcer-delivery apparatus could wavetramp and demodulate microwave energy leading to noxious, experimentally confounding stimulation of the S. Like considerations led to this report: we needed a system for presenting unavoidable footshock in the microwave field that would not contaminate measurement of behavior or harm a rat during protracted studies of conditional suppression.

Repeated presentations of footshock from gridbars of fixed polarity often result in an experimental animal's learning to avoid such stimulation by standing on one rod or upon two rods of common electrical potential. Recourse to scrambling circuitry (Skinner & Campbell, 1947) was not sought because a multiplicity of electrical conductors coursing between shockgrid and an external source of stimulating current could lead to

escape of RF energy and confounding of dosimetry. The use of neon lamps in series with an array of rods (Markowitz & Saslow, 1964) would reduce the number of externally connected conductors, but was contraindicated because microwave energy lowers the ionizing potential of noble gasses and would impair the regulatory capability of a neon-discharge system. Too, neon lamps intermittently illuminate under moderate power levels of pulsed irradiation and would create a visual

distraction for an irradiated animal. Finally, stimulation via chronically implanted skin electrodes (cf. Kelly & Glusman, 1964; Campbell & Moorcroft, 1970) could not be used because external leads connecting to the animal would likely wavetramp RF energy and produce noxious stimulation.

The problem was resolved by a faradic source of stimulation whose oldest electrophysiological antecedent is the induction coil of du Bois Reymond (Brazier, 1961). Marconi subsequently made use of the principle in his wireless telegraphy; his "spark-gap" transmitter was able to broadcast electromagnetic energy over great distances. Our aim was similar but more modest: to secure a source of energy that would "jump the gap" between animals and shockgrid irrespective of their posturing and attempts at avoidance.

Circuitry

The ignition coil developed by Henry Ford for his Model T automobile is an elaboration of the faradic principle and, since the coil is still available for purchase,¹ it formed the basic element of our stimulator. As seen in

PARTS LIST

- C₁ .47 μ F 200 V DC CAPACITOR
- C₂, C₃ .002 μ F 600 V DC CAPACITOR
- C₄ .01 μ F 200 V DC CAPACITOR
- C₅ 500 pF 20 KV CAPACITOR
- CH₁ CHASSIS: 1-BUD #1372; 2-BUD #PA1103
- CO₁ CO-AXIAL CABLE: COLUMBIA "FLEXFOAM" #1399, 113 CM LENGTH
- F₁ 1/2 AMPERE FUSE
- K₁ POTTER & BRUMFIELD KRP-14-DG RELAY
- L₁, L₂ 1mH RF CHOKE
- L₃ 1mH RF CHOKE
- L₄, L₅, L₆ 2.5 μ H RF CHOKE
- P₁ STANDARD 3-PRONG POLARIZED LINE PLUG
- R₁ 4.7 Ω 1/2 WATT RESISTOR, $\pm 10\%$
- R₂ 470K Ω 1/2 WATT RESISTOR, $\pm 10\%$
- S₁ SOLID-STATE, PROGRAMMABLE SWITCH, E.G., LVE #1841
- T₁ 115-5 VAC STEPDOWN XFORMER, E.G., CH₁ #P6458 FIL. XFORMER
- T₂ IGNITION COIL: J.C. WHITNEY #16-195

Fig. 1. Schematic and parts list of faradic stimulator.

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Fig. 2. Photograph of faradic stimulator (at reader's right) and microwave apparatus. A photooperandum and a reinforcer delivery system have been removed (see King, Justesen, & Simpson, 1970) to permit a clearer view of the operant conditioning chamber located within the exposure cavity. The looped (coaxial) cable conveys current from the stimulator to the cavity; the two smaller wires running to the stimulator provide operating voltage for Relay K_1 from a control panel (not shown). The cable leading to the viewing window of the door to the cavity is from a shielded thermistor that is used to monitor ambient temperature in the operant chamber.

the schematic of Fig. 1, the primary winding of the coil is driven (at 5 V) by a stepdown transformer (T_1) coupled to a 115-V ac power line. The primary of the coil (T_2) is wound around an iron core whose electromagnetic field actuates a commutator switch. Actuation of the commutator opens the switch and removes current from the primary, leading to a collapse of the magnetic field and a reclosing of the switch. The cycle is repeated, and the result is a rapidly pulsed inductive excitation of the high-voltage, secondary winding of the coil. If irregularly pulsed dc current were presented to the primary, "white noise" in the electrical sense would appear across the secondary (square waves, by definition, possess an infinite number of odd harmonics). Because interrupted ac excites the primary, the broadband RF signal appearing across the secondary is more properly described as a "gray" or "dirty" noise. But RF noise it is, and the raw output of the secondary must be processed to rid it of much potential mischief. Not only would energy be radiated, it would be dumped into the power line, and either form of transmission would incur the wrath of the FCC, not to mention would-be listeners to AM radio. Solid-state devices plugged into the power line would not only

malfunction but be in danger of irreversible damage from high-voltage transients.

The power line is isolated from RF energy by series chokes L_1 and L_2 and shunt capacitors C_2 and C_3 . Airborne broadcast is controlled by RF chokes L_3 - L_6 and shunt capacitors C_4 and C_5 . To prevent induction to and leakage from external leads to the control relay, K_1 , the leads are twisted tightly and mounted close to the chassis. The chassis itself completely encloses main circuit elements and functions as an electrical shield (see Fig. 2).

The coaxial cable by which current is conducted from the stimulator is a critical element in the circuit. Any coaxial conductor is a shunt capacitance to its source of current, and thus its length inversely determines the amount of capacitive reactance presented to the source. The lower the reactance, the greater the shunting effect on higher frequency energy. We determined the appropriate length empirically (113 cm) by successively shortening the cable until the desired level of stimulation was achieved.

The final critical element of the shock circuit is the resistor, R_2 . By placing nearly half a million ohms in series with the high-voltage output, we obtained limiting of output current

and controlled for shock hazard to laboratory personnel.²

Shockgrid and Connections

Figure 3 presents a rear view of an operant chamber, the aluminum grid rods of which are insulated and mounted flush at the front but protrude through the rear to make contact with a connector panel. The panel is formed from a 36.2 x 3.8 x 0.635 cm block of low-loss plastic with 19 fuse clips mounted at 2.54-cm intervals. Each clip makes a tight connection with 1 of the 19 (0.635-cm-diam) rods making up the shockgrid. Every second clip is bolted to a lug that is soldered to a 1.59-mm-diam bus bar of brass; each alternate clip, to a lug soldered to a second bus bar. With attachment of the connector panel and installation of the chamber in the exposure cavity, 9 of the 19 rods are grounded to the metallic shell of the cavity by a spring contact suspended from one bus bar. The bus bar linking the 10 remaining rods is soldered to a length of insulated test lead that is dressed closely to the cavity surface and terminates in a banana plug. The plug is inserted into a banana jack on the inside of the door to the exposure cavity (shown in the open position in Fig. 3). Within the hollow space of the door, the contact lug of the banana jack is soldered to a series circuit comprising a 100-k-ohm, $\frac{1}{2}$ -W resistor interposed between two 2-mH RF chokes. The distal connection is soldered to the medial connector of a coaxial jack mounted on the outside of the door.³ The coaxial cable from the stimulator plugs into the coaxial jack, the shielding of the cable being grounded thereby to the metallic surface of the door.

Introspective and Behavioral Characterization of the Stimulus

Before electrical measurements and formal behavioral assessment of the faradic stimulus were undertaken, we explored first with our own fingers and then with naive animals its affective properties. Shock voltage was automatically and aperiodically presented across alternate grid bars for 0.5-sec durations. Each of us individually placed an index and middle finger of one hand upon an adjacent pair of rods prior to presentation of shock. The sensation produced by the stimulus could not be called painful, even as we cut the length of the coaxial cable to increase intensity of stimulation. The stimulus is better described as startling, both initially and after repeated presentations. The sensation was akin, only more sustained, to that encountered by walking across a plush

Fig. 3. The operant conditioning chamber was removed from the exposure cavity, the back wall of the chamber facing the reader. The connector panel is shown with its two parallel bus bars that make contact with alternate rods of the shockgrid. The arrow to the reader's left points to a banana jack on the inside of the door to the cavity; the jack connects with a coaxial jack on the external surface of the door and is the internal point of connection for the single lead that conveys motivational current to the alternate bars of the shockgrid. The remaining bars are automatically grounded to the metallic shell of the cavity by a spring contact when the operant chamber is mounted within.

carpet and touching the metallic object that receives a static discharge. We found it impossible to maintain contact with the shockgrid because of involuntary motor activity evoked by the stimulus. This activity was subsequently observed in experimentally naive rats placed upon the grid and individually subjected to the same schedule of aperiodic shock. All animals initially reacted with a violent start, jumped into the air, and vocalized. After repeated presentations the vocalization abated, but evoked motor activity did not. Even though shock only was presented to the grid for 0.5-sec intervals, the animals literally jumped into the air between onset and termination of voltage application. In spite of this intermittent escape from stimulation, no animal was ever observed, even during half a year of subsequent, near daily encounters with multiple shocks, to avoid the initial segment of the stimulus. On occasion, an animal would roll on its back or make other movements suggestive of attempted avoidance, but startle and intense motor activity were invariably evoked upon activation of stimulating circuitry. We looked for but never observed electrical sparks jumping between grid rod and animal. Apparently the tail or the pelt (both highly resistive to conventional current flow) are sufficient for suprathreshold stimulation.

Electrical Characterization of the Stimulus

Upon achieving the desired level of motivational shock, each of several deeply anesthetized rats was placed in the operant chamber. Anesthetization was necessary to control for pain and to insure relatively prolonged contact between animal and shockgrid while measurements were being made. Relay K₁ was activated, and stimulation was continuously presented while an animal's hindlimbs contacted a pair of rods of opposing polarity. Voltages were measured across the same pair of rods by a Simpson Model 601-1 solid-state ac/dc volt-ohm-milliammeter (VOM) and a Dumont Model 401-A oscilloscope. Measurement of current was accomplished by removing the banana plug of the high-voltage lead and interposing the test leads of the Simpson VOM between jack and plug.

Peak voltages, as measured across a voltage-dividing network with the oscilloscope, reached a maximum of 1.2 kV; rms values registered on the VOM ranged from 10 to 95 V and from 700 to 895 microA as we gently pressed upon and released an animal to simulate normal shifts of impedance through change of contact pressure. Mean values were 31 V and 860 microA. Because of distributive capacitance between grid bars and other metallic elements of the

connector panel (measured at 140 pF by a capacitance bridge), the output current, as measured, flows through two parallel pathways, the animal S and the reactive load of the shockgrid ensemble. We extrapolated net current values flowing through an animal by removing it from the shockgrid and (1) measuring rms voltage across (300 V) and current through (400 microA) the unloaded grid; (2) obtaining an approximation of the shockgrid's impedance (750 k ohms) by dividing the voltage by the current; then (3) establishing the range of the animal Ss' impedances (11 k to 200 k ohms) in consequence of the observed range of voltages dropped across them while they were in parallel with the 750-k-ohm load. With application of Ohm's law, the extrapolated rms range is 550 to 860 microA, and the average current flowing through an animal, 790 microA. The mean observed voltage drop of 31 V indicates the animals were presenting an average impedance to the shock source of approximately 40,000 ohms.⁴

To gain some idea of the distribution of stimulus frequencies present at the shockgrid we observed the oscilloscope at different sweep rates at the time of measuring peak voltages. Only negligible energy above 10 kHz was seen. Nominal frequency, the hypothetical single-frequency signal that would generate a reactance (X_c) of 750 k ohms across the empty shockgrid with a capacitance (C) of 140 pF, was found by taking the reciprocal of $2\pi CX_c$ and is close to 1,500 Hz. With an animal on the grid bars, the nominal frequency would drop somewhat because of capacitive loading.

Operation in a Microwave Field

The carrier frequency of the microwave generator used in our apparatus is $2,450 \pm 50$ MHz. While the 140-pF distributive capacity of the shockgrid ensemble presents a relatively high shunt impedance to the low RF shock current, the impedance presented to the ultra-high-frequency (UHF), 2,450-MHz field is minuscule.⁵ In effect, all 19 grid rods are rendered isoelectric to impinging microwave energy. Further, the rods are placed at a potential common to the metallic shell of the exposure cavity because 9 of the 19 rods are continuously grounded to the shell.⁶

Behavioral Assessment of the Faradic Stimulus

Three albino rats, adult males supplied by Simonsen of Minnesota, were fed to 75% of preexperimental weights. They were then placed on a running food-deprivation schedule in

Fig. 4. Segment a (two tracings at top) reflects operant responding of two rats, R₅ and R₂, in the presence of a 525-Hz tone. The records were obtained during early control sessions before gridshock was presented, while the animals were being adapted to "novel-stimulus" effects. Segment b reflects operant responding by the same rats during early attempts to condition suppression of operant behavior. The middle tracings reflect performances during the first and last presentations of motivational shock in the first experimental session, and the bottom tracings, performance during the 11th session. A single hatchmark in the horizontal line above a tracing signals presentation of footshock, and the sustained hatch in the line below, a 1-min interval of tonal cueing.

which each animal was thereafter fed to match 75% of the median weight gain across time of three freely fed littermates. At commencement of experimental sessions, the animals weighed from 487 to 513 g. Each session was 120 min in duration. Sessions were generally conducted daily, never more often, across a

6-month interval of study. The ongoing operant task upon which warning stimuli and gridshock were superimposed has been described elsewhere (King, Justesen, & Simpson, 1970) but essentially involved photodetection of operant tongue-licking, and payoffs by 30-microliter reinforcers of

sugar-water (16% w/v) on low-demand variable-interval schedules.

In all, each animal individually participated in a total of 149 sessions, 65 of which involved presentations of footshock. Within each session, when programmed, footshock was presented aperiodically a total of eight times. Voltage was applied to the shockgrid

for 0.5 sec. Generally, either a 525-Hz tone or microwave irradiation was presented as a warning stimulus immediately preceding footshock. Since the microwave data will be presented elsewhere (King, Justesen, & Clarke, 1971), we shall address ourselves to findings based upon auditory cueing.

After conducting sessions in which novel stimulus effects were adapted and tests for sensitization and pseudoconditioning completed, each rat was scheduled for a block of eight sessions in which the warning tone heralded footshock. Continuous counts were made of the number of licking responses emitted during a "safe" 60-sec interval immediately preceding the warning tone, and the number emitted during the 60-sec warning interval. Percent efficiency of discrimination was calculated by the formula $[(S - W)/S] \times 100$ (where S = total number of responses emitted during safe intervals and W = total number during warning intervals). The three animals, R_1 , R_2 , and R_5 , respectively, generated discriminative efficiencies of 97%, 95%, and 98%. Approximately 5 months later, following intervening experiments with tonal cueing or microwave irradiation as the warning stimulus, a second block of four sessions was conducted with tone as the warning stimulus. Discriminative efficiencies remained high, between 92% and 95%. At the end of 6 months, resistance to extinction was measured during two sessions. When the warning tone was presented without footshock, animals R_1 , R_2 , and R_5 , respectively, generated discriminative efficiencies of 80%, 92%, and 99%.

The effectiveness with which conditional suppression was brought about can be seen in segments of cumulative records presented in Fig. 4. The records shown are highly representative of performances during the earliest stages of conditioning. Even during the eight initial trials of conditioning there is evidence of conditional suppression. By the 11th session and after 90 trials, efficiency

of suppression approached 100% in all three animals.

Discussion

The faradic source of motivational shock described in this paper met two necessary behavioral criteria with respect to promotion of conditional suppression: (1) the stimulus is unavoidable—even over protracted intervals of stimulation; and (2) the stimulus proves neither so weak as to be unreliable nor so intense as irreversibly to inhibit operant responding after repeated application. Few investigators are likely to be faced with the difficulties incumbent with studying operant behavior in a microwave field, but many have had to deal with problems of behavioral stability or stimulus control incumbent with conventional sources of shock as used in operant and respondent conditioning procedures. The faradic stimulus appears to overcome both of these problems. Investigators who would combine the faradic footshock with electrophysiological measurement are warned, however, that polygraphs and other voltage-sensitive devices will be inundated with electrical noise unless shielding and isolation are carefully implemented.

Oke (1971) recently used the faradic stimulator to produce one-trial avoidance learning in rats. It was necessary to increase output current, which Oke accomplished by substituting two separate leads for the coaxial cable and reducing the overall limiting resistance in the high-voltage secondary by 20%. A continuously controlled range of output currents could also be realized through a rheostat in the primary of the stepdown transformer, T_1 . The schematic presented in Fig. 1 indicates where the rheostat would be inserted into the circuit.

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NOTES

1. From J. C. Whitney & Co., 1917 Archer Avenue, Chicago, Illinois 60616; Catalog No. 16-195 (\$5.39).
2. Another 100-k-ohm resistor, located in the microwave apparatus, is in series between shock source and shockgrid, thus raising the total limiting resistance to nearly 600 k ohms.
3. The two RF chokes would offer little nominal impedance to the stimulus current (~ 40 ohms) but much greater impedance to the 2,450-MHz microwaves ($\sim 6 \times 10^7$ ohms); the purpose of the chokes is to block leakage of microwave energy from the exposure cavity.
4. All the rms current and voltage values as given are rough approximations in view of the unknown (capacitive and inductive) reactive properties of the Simpson VOM. While the reactive loading properties are probably not too great, the values are better taken in the operational sense, i.e., "this is what one observes when one uses the measuring instruments specified." Oscilloscopic measurement of peak voltages is also operationally qualified because of unknown loading influences.
5. Capacitive reactance (X_C) in ohms was estimated by the formula $X_C = 1/(2\pi fC)$, where f = frequency in hertz, and C , capacity in farads.
6. We did not beg the empirical question of the shock grid's intertiness to microwaves, but ruled out in several experiments the possibility that the animals were affected by demodulated RF energy. The data are presented in King, Justesen, & Clarke (1971).