

A Low-Cost Neurostimulator With Accurate Pulsed-Current Control

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Abstract—A constant-current stimulator for high-impedance loads using only low-cost standard high-voltage components is presented. A voltage-regulator powers an oscillator built across the primary of a step-up transformer whose secondary supplies, after rectification, the high voltage to a switched current-mirror in the driving stage. Adjusting the regulated voltage controls the pulsed-current intensity. A prototype produces stimulus of amplitude and pulsewidth within $0 \leq I_{\text{skin}} \leq 20$ mA and $50 \mu\text{s} \leq T_{\text{pulse}} \leq 1$ ms, respectively. Pulse-repetition spans from 1 Hz to 10 Hz. Worst case ripple is 3.7% at $I_{\text{skin}} = 1$ mA. Overall consumption is 5.6 W at $I_{\text{skin}} = 20$ mA.

Index Terms—Current source, current stimulator, electrocutaneous stimulation, high voltage.

I. INTRODUCTION

Lesions in the nervous system that provoke disruption in the flow of sensory and motor signals to the brain and spinal cord may cause neurological handicaps. Functional neuromuscular stimulation (FNS) is the electrical activation of paralyzed muscles and can be applied to restore partial functionality while providing a medical diagnosis of the nervous system. FNS is embedded in many prosthetic devices aiming different applications such as control activity of motor nerves and urinary bladder, pain relief, stroke victims, etc. [1].

Surface stimulators handing over voltage pulses do not guarantee a preset current intensity as the delivered current changes with the characteristic of the electrode/skin load. Current-regulated bursts are therefore most preferred since the charge transferred per stimulus is constant regardless the load impedance [2]–[4]. Besides, no uncontrolled spikes occur at the current-step onset. On the current-pump stimulator reported by Poletto *et al.* [5], the V/I converter relies on costly op-amps, as they should meet stringent high-voltage (HV) tolerance and slew rating, while demanding special care for frequency compensation and over-voltage/current protection. The output stage requires five power-supply modules so that a power-up management is needed to establish their turn-on sequence, at expense of circuit complexity and consumption. The sample-and-hold current sink/source presented by Hochmair [6] lacks accuracy, as the current intensity set by the sampled voltage depends on the bulk effect of metal–oxide–semiconductor field-effect transistors. On the approach by Kaczmarek *et al.* [7], the current is derived from a reference voltage and mirrored to the output. However, the driving stage is supplied by on-board fixed-value HV sources, which remain active even on the absence of a stimulus current. Stand-by consumption is thus increased due to ac/dc conversion. An HV version of the implanted stimulator by Gudnason *et al.* [8] would also experience such a drawback as fixed supplies power the current mirrors.

This communication describes a constant-current neuromuscular stimulator employing only standard HV components, whereas featuring good controllability of stimulus variables such as amplitude,

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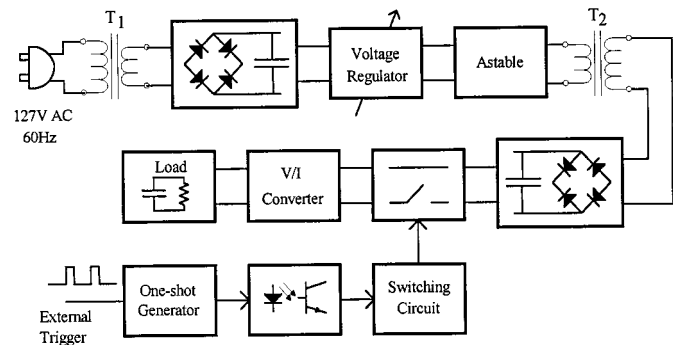


Fig. 1. Block diagram of the neurostimulator.

duration, and frequency of the pulsed current. Its small number of components makes it appropriate for low-cost applications. In contrast with [5]–[8], the supply voltage in the driving stage is proportional to the stimulus current. Power consumption is then reduced, which is attractive for battery-operated systems.

II. DESCRIPTION OF THE NEURAL STIMULATOR

The block diagram of the neurostimulator is shown in Fig. 1. It consists of a pair of transformers with full-bridge rectifiers, a voltage-regulator, an astable multivibrator, a photocoupler, and a driving stage, which is composed by a switching circuit and a V/I converter. The load represents both resistive and reactive components of the electrode/skin interface as well as the bulk tissue resistance [3].

The circuit operates as follows. Line transformer T_1 and rectifier feed a voltage-regulator, whose output V_R sets the astable supply-voltage. Since the astable is loaded by the primary of step-up transformer T_2 , a self-excited HV oscillation across the secondary windings is attained [9], [10]. After rectification and filtering, a high dc voltage, which is therefore proportional to V_R , is supplied to a switched V/I converter built upon a cascode current-mirror that delivers to the load a pulsed current with constant amplitude. Pulse duration is externally determined by a monostable, which is triggered by a transistor–transistor logic level signal. The resulting one-shot pulse is input to a photocoupler that drives a switching circuit made up of discrete transistors.

The oscillator schematic is illustrated in Fig. 2. Transformer T_1 (6:1, 15 VA) lowers the power-line voltage from 127 $V_{\text{ac rms}}$ to 30 V_{peak} . The full-bridge rectifier comprises diodes D_1 – D_4 (1N4007) and filter-capacitor C_1 . The resulting dc voltage supplies the voltage-regulator (LM317T). Ultimately, the stimulus magnitude is proportional to V_R , which is manually adjusted by potentiometer R_2 in the present design. Nevertheless, advanced versions of the stimulator may feature a programmable adjustment. Diodes D_6 – D_9 (1N4007) produce the voltage drop that ensures 0 V as the lowest V_R supplied to the astable, which comprises BJT devices Q_1 – Q_2 (TIP41C), base resistors R_3 – R_4 and collector-coupling capacitors C_4 – C_5 . Since oscillation takes place across the center-taped primary of step-up transformer T_2 , a HV oscillation is developed at its secondary. Supply voltages V_{DDO}^+ and V_{DDO}^- are available after ac/dc conversion by the bridge D_{10} – D_{13} (1N4007) and C_7 .

Fig. 3 displays the driving-stage schematic, based on a self-biased current mirror formed by MOS transistors M_1 – M_4 (MPT2N60). R_E and C_E are the components of the electrode/skin interface and R_S is the tissue resistance. Fixing R_5 and denoting $V_{\text{DDO}} = V_{\text{DDO}}^+ - V_{\text{DDO}}^-$, it comes out $I_{\text{skin}} = (V_{\text{DDO}} - V_{\text{GS1}} - V_{\text{GS3}})/R_5$. Both V_{DDO} and R_5 set the stimulus current, which is load-independent at good extension.

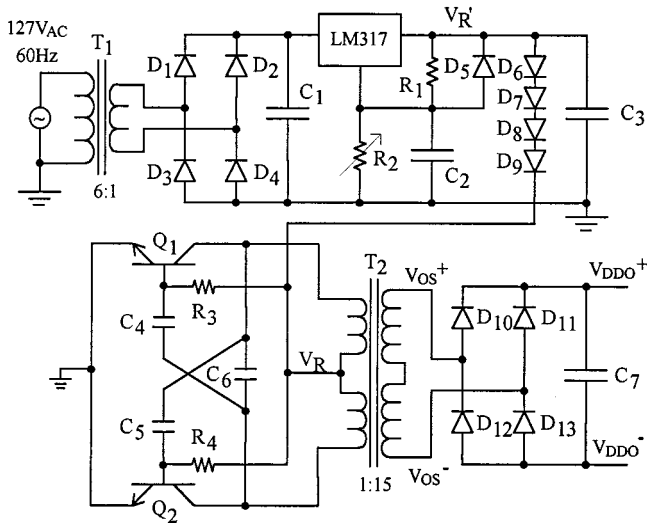


Fig. 2. Oscillator schematic.

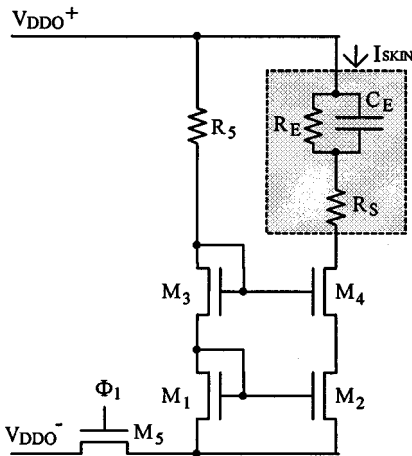


Fig. 3. Driving-stage schematic.

Upon assertion of phase Φ_1 , M_5 switches on current mirroring, so that a pulsed current is output by the stage.

III. CIRCUIT DESIGN

The circuit was sized to deliver currents of amplitude and pulsewidth within $0 \leq I_{\text{skin}} \leq 20$ mA and $50 \mu\text{s} \leq T_{\text{pulse}} \leq 1$ ms, respectively. Pulse-repetition ranges from 1 Hz to 10 Hz, while the ripple associated with I_{skin} is limited to 6%. It is worth noticing that the proposed topology does not restrict the amplitude of I_{skin} to the specified range, which can be extended by increasing the number of turns in T_2 and using components with higher voltage specifications. As the external circuitry imposes pulsewidth and stimulation rate, such parameters can be easily adjusted, despite the current magnitude.

Considering the use of electrodes with small surface areas, a maximum value of 10 k Ω was assumed for the highly nonlinear resistance $R_{\text{ES}} = R_E + R_S$ that mimics the electrode and tissue resistances. Adopting $R_5 = 10$ k Ω and accounting for voltage drops $V_{\text{DSAT}2}$, $V_{\text{DSAT}4}$ and $V_{\text{DS}5}$ in the driving stage, a compliance voltage $V_{\text{DDO}} = 210$ V assures current mirroring at highest stimulus current. Therefore, the oscillation at the secondary of T_2 must reach 420 V_{pp} . As nominal characteristics, T_2 exhibits a winding-ratio of 1:15, a primary-inductance of 53 mH, a 4-kV isolation and maximum dissipation of 10 VA. By adjusting V_R from 0 to 12 V, peak amplitudes from 0 to 220 V are attained at the secondary of T_2 .

Design constraints on sizing C_7 are twofold: 1) the minimum energy per a pulsed stimulus and 2) the highest allowed ripple on I_{skin} . Neglecting the consumption on current-mirror transistors, the energy to be delivered by C_7 is $E_{\text{tot}} \cong E_{\text{opt}} + 2R_{\text{ES}}I_{\text{skin}}^2T_{\text{pulse}}$, where E_{opt} is the optocoupler term. Direct manipulation leads to $C_7 \geq 2(2 + \eta)T_{\text{pulse}}/R_{\text{ES}}$, where $\eta = I_{\text{opto}}/I_{\text{skin}}$ and I_{opto} is the optocoupler output-current. C_7 should thus be sized in accordance with the largest pulsewidth and smallest amplitude of I_{skin} .

An initial characterization of I_{opto} as function of I_{skin} was carried out, although it is here omitted for the sake of conciseness. Taking $T_{\text{pulse}} = 1$ ms and $I_{\text{skin}} = 1$ mA, it comes out $I_{\text{opto}} = 4.6$ mA, so that $C_7 \geq 1.33$ μF . The ripple factor is given by $[1 - \exp(-T_{\text{pulse}}/\tau)]$, where $\tau = R_L C_7$ and $R_L \cong R_{\text{ES}}/R_5/R_{\text{opto}}$ is the filter resistive-load. R_{opto} denotes the dc-resistance $V_{\text{DDO}}/I_{\text{opto}}$ of the optocoupler branch. For the specified ranges of V_{DDO} and I_{skin} , one has 1.95 k $\Omega \leq R_L \leq 4.1$ k Ω . Adopting $C_7 = 8.8$ μF , calculated ripple factors are 5.66% at $I_{\text{skin}} = 1$ mA and 2.73% at $I_{\text{skin}} = 20$ mA, for worst-case pulsewidth of 1 ms. Larger values of C_7 decrease the ripple, at expense of higher overall consumption, however.

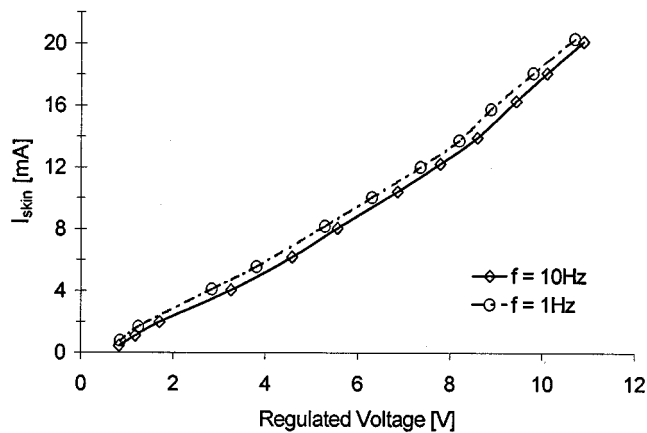
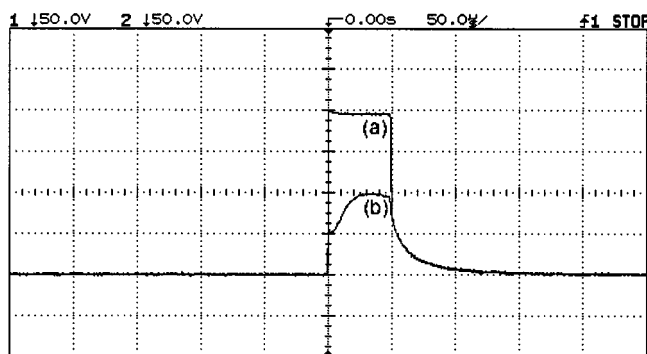
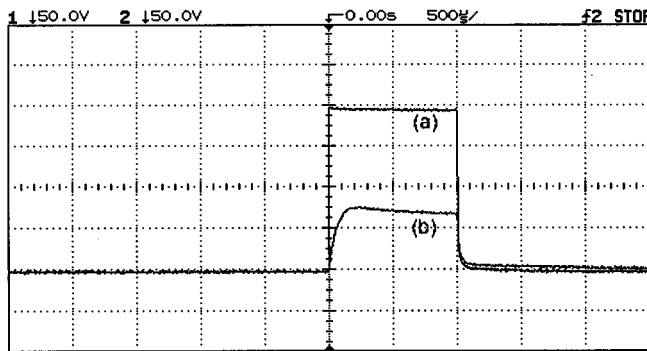
Assuming the astable generates a square waveform and approximating the analysis to the case of a purely resistive load between the collectors of Q_1 and Q_2 , the oscillation period is $T_a \cong -2R_3C_X \ln[(V_R - V_{\text{BE}})/(2V_R + V_{\text{BE}} - V_{\text{CEsat}})]$, where C_X represents the series association of C_4 and $(1/2)C_6$. By choosing $R_3 = R_4 = 10$ k Ω , $C_4 = C_5 = 0.47$ μF and $C_6 = 2.2$ μF , preliminary measurements indicated an oscillation-frequency interval of 170 Hz $\leq f_a \leq 199$ Hz, for 1 V $\leq V_R \leq 12$ V. While still complying with the specified ripple on I_{skin} , such a low-frequency oscillation reduces the astable consumption, and consequently, the current required from the voltage-regulator. Pulsewidth spans from 50 μs to 1 ms and is adjusted in the external monostable. Other components are $R_7 = 1$ k Ω , $R_8 = R_{10} = 10$ k Ω , $R_{11} = 1$ k Ω and $C_8 = C_9 = 1$ μF .

IV. EXPERIMENTAL RESULTS

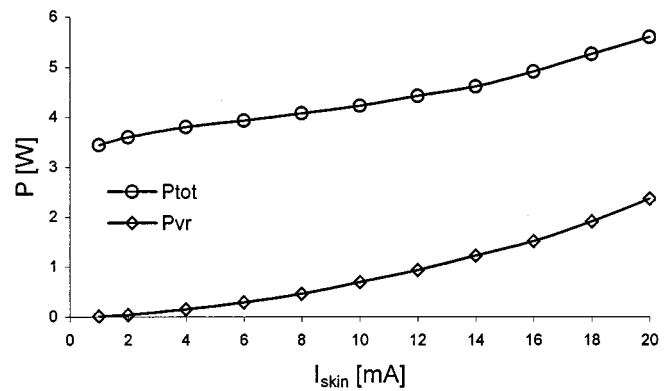
A wire-wrapped prototype of the neurostimulator was realized. All resistors are 1/4 W-carbon with 5%-tolerance. In order to appraise the stimulator limits without the restriction imposed by subject pain-threshold, a 10 k Ω -load resistor was initially set as R_{ES} . The transfer function of the circuit, defined as the amplitude of the load current against the voltage-regulator output, is displayed in Fig. 4, for stimulation rates of 1 Hz and 10 Hz. For $I_{\text{skin}} = 20$ mA, amplitude and frequency of oscillation across the secondary of T_2 are 438 V_{pp} and 204 Hz, respectively. Current mirroring was also characterized over the specified current interval, with relative errors below 5%. Fluctuation of V_{DDO} as function of load resistance was found less than 2%, for $0 \leq R_{\text{ES}} \leq 10$ k Ω .

Prior to stimulation, the skin of the subject's wrist was abraded and an electrolyte gel applied to improve contact with the electrode leads. Tests were performed at different stimulation ratings. At $I_{\text{skin}} = 20$ mA and an interpulse separation of 0.1 s (10 Hz), the voltage waveforms across $R_5 = 10$ k Ω (a) and skin electrodes (b) are shown in Fig. 5, for $T_{\text{pulse}} = 50$ μs . As it can be seen, a reference current of 20 mA flows through R_5 and is mirrored to the load. On steady state, the voltage difference between electrodes reaches 100 V, so that a value of 5 k Ω is estimated for R_{ES} . Similar waveforms are presented in Fig. 6, for $T_{\text{pulse}} = 1$ ms. In this case, the voltage across terminals is nearly 70 V, so that R_{ES} decreases to 3.5 k Ω . Pulse fall-time is shorter than 42 μs , which makes the circuit compatible to relatively high stimulation rates.

For a 1-ms pulsewidth, the measured ripple is 3.7% at $I_{\text{skin}} = 1$ mA and 1.9% at $I_{\text{skin}} = 20$ mA. Overall power consumption P_{TOT} as function of I_{skin} is displayed in Fig. 7. Since battery-operated devices

Fig. 4. Measured amplitude of I_{skin} as function of regulated voltage V_R .Fig. 5. Voltage across $R_5 = 10k\Omega$ (a) and skin electrodes, (b) at $I_{skin} = 20$ mA and $T_{pulse} = 50 \mu s$. A reference current of 20 mA is set by R_5 and mirrored to the load. Estimated value for R_{ES} is 5 kΩ (vert.: 50 V/div, horiz.: 50 μs/div).Fig. 6. Voltage across $R_5 = 10k\Omega$ (a) and skin electrodes, (b) at $I_{skin} = 20$ mA and $T_{pulse} = 1$ ms. A reference current of 20 mA is set by R_5 and mirrored to the load. Estimated value for R_{ES} is 3.5 kΩ (vert.: 50 V/div, horiz.: 500 μs/div).

are also focused, the voltage-regulator consumption is examined. From rms values of voltage and current at the LM317T output, the power P_{VR} delivered by this component was evaluated. For a total consumption of 5.6 W at $I_{skin} = 20$ mA, the LM317T hands over 2.36 W. Stand-by consumption is 3.1 W and accounts for the dissipation in line transformer and rectifier, as the astable develops no oscillation. Consequently, the remaining 2.5 W imply that 94.4% of the power delivered by the voltage-regulator is dissipated in the active part of the circuit. Such efficiency makes the stimulator suitable for portable equipment, in which batteries would directly power the voltage-regulator. The measured parameters of the stimulator are summarized in Table I.

Fig. 7. Power dissipation as function of I_{skin} (P_{TOT} : total consumption; P_{VR} : power delivered by the voltage-regulator).TABLE I
NEUROSTIMULATOR MEASURED CHARACTERISTICS

	Min	Max
Output Current (mA)	0	20
Pulse Duration (μs)	50	1000
Fall Time (μs)	-	42
Ripple (%)	1.9	3.7
Stimulation Rate (Hz)	1	10
Consumption (W)	3.4	5.6

V. CONCLUSION

A low-cost constant-current neurostimulator based on standard HV components was presented. It comprises a voltage-regulator that powers an oscillator built across the primary of a step-up transformer, whose secondary supplies, after rectification, the high voltage to a switched current-mirror in the driving stage. As such a voltage is proportional to the stimulus current, stand-by consumption is basically limited to the ac/dc conversion that supplies the voltage-regulator. Adjusting the regulated voltage controls current intensity, whereas an optically coupled monostable sets the pulsewidth.

A prototype with readily available components generates currents of amplitude and pulsewidth within intervals $0 \leq I_{skin} \leq 20$ mA and $50 \mu s \leq T_{pulse} \leq 1$ ms, respectively, for stimulation rates from 1 Hz to 10 Hz. At maximum consumption of 5.6 W, the voltage-regulator delivers 2.36 W. Stand-by consumption is 3.1 W. Largest ripple is 2.5% for $4 \text{ mA} \leq I_{skin} \leq 20$ mA. Subject isolation from power line is 4 kV.

Although the circuit was originally devised to muscular stimulation through surface electrodes and sized for a maximum electrode/skin resistance of 10 kΩ, the proposed topology can be applied to other ranges of stimulators. The use of a step-up transformer with an increased ratio of windings and components with higher voltage specifications would accommodate larger values of stimulus current and skin resistance. The small number of components and low consumption make the stimulator valuable for portable applications.

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Correction to "How Electrode Size Affects the Electrical Potential Distribution in Cardiac Tissue"

Bradley J. Roth

The numerical simulation in the above paper [1] contains an error caused by a mistake in the computer program, which changes the quantitative but not qualitative results. The revised Figs. 3 and 4 are shown here. In Fig. 4, the ratio $D_{\text{peak}}/H_{\text{peak}}$ for large electrodes approaches a value of about 30, which is significantly larger than the value of about 3 in the original manuscript, and implies that the model is less likely to explain the experimentally observed ratio of anodal and cathodal thresholds.

The author would like to thank D. Janks of the Department of Physics, Oakland University, for pointing out this error.

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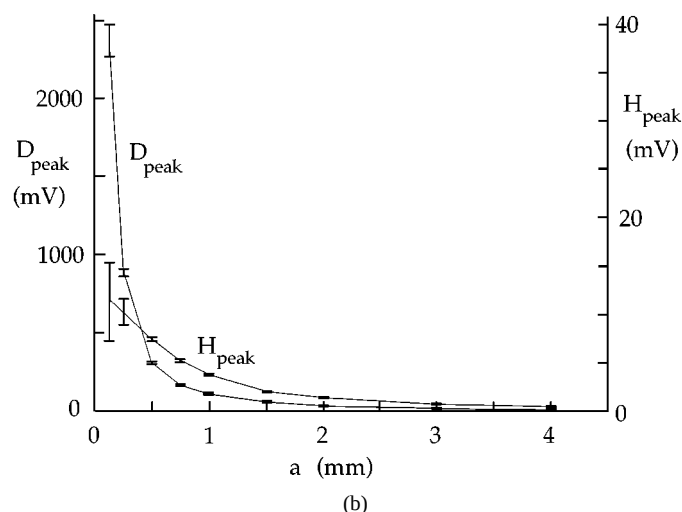
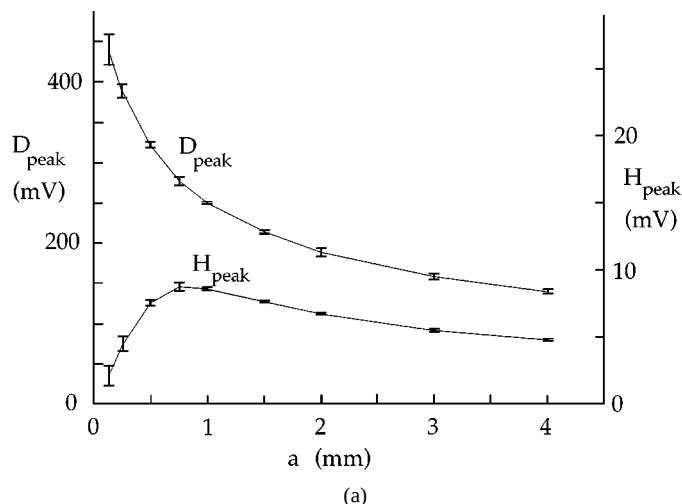


Fig. 3. Plot of peak depolarization, D_{peak} , and peak hyperpolarization, H_{peak} , vs. electrode radius, a , for (a) constant voltage (1 V), and (b) constant current (0.1 mA). The error bars represent the difference between the results for $N = 199$ and the results for $N = 159$.

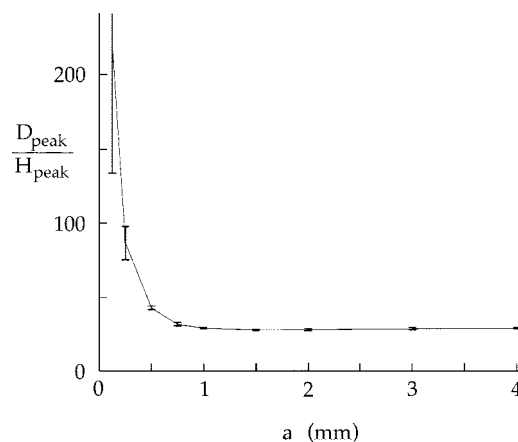


Fig. 4. Plot of the ratio of peak depolarization to peak hyperpolarization, $D_{\text{peak}}/H_{\text{peak}}$, as a function of electrode radius, a . The error bars represent the difference between the results for $N = 199$ and the results for $N = 159$.

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