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# A Low Power Micro Deep Brain Stimulation Device for Murine Preclinical Research

ABBAS Z. KOUZANI (Member, IEEE)<sup>1</sup>, OSAMA A. ABULSEUD<sup>2</sup>, SUSANNAH J. TYE<sup>2</sup>,  
MD KAMAL HOSAIN (Student Member, IEEE)<sup>1</sup>, AND MICHAEL BERK<sup>3</sup>

<sup>1</sup>School of Engineering, Deakin University, Waurn Ponds, Victoria 3216, Australia

<sup>2</sup>Department of Psychiatry and Psychology, Mayo Clinic, Rochester, MN 55905, USA

<sup>3</sup>School of Medicine, Deakin University, Waurn Ponds, Victoria 3216, Australia

CORRESPONDING AUTHOR: A. Z. KOUZANI (kouzani@deakin.edu.au)

**ABSTRACT** Deep brain stimulation has emerged as an effective medical procedure that has therapeutic efficacy in a number of neuropsychiatric disorders. Preclinical research involving laboratory animals is being conducted to study the principles, mechanisms, and therapeutic effects of deep brain stimulation. A bottleneck is, however, the lack of deep brain stimulation devices that enable long term brain stimulation in freely moving laboratory animals. Most of the existing devices employ complex circuitry, and are thus bulky. These devices are usually connected to the electrode that is implanted into the animal brain using long fixed wires. In long term behavioral trials, however, laboratory animals often need to continuously receive brain stimulation for days without interruption, which is difficult with existing technology. This paper presents a low power and lightweight portable microdeep brain stimulation device for laboratory animals. Three different configurations of the device are presented as follows: 1) single piece head mountable; 2) single piece back mountable; and 3) two piece back mountable. The device can be easily carried by the animal during the course of a clinical trial, and that it can produce non-stop stimulation current pulses of desired characteristics for over 12 days on a single battery. It employs passive charge balancing to minimize undesirable effects on the target tissue. The results of bench, *in-vitro*, and *in-vivo* tests to evaluate the performance of the device are presented.

**INDEX TERMS** Deep brain stimulation, long-term stimulation, low-power lightweight device, stimulation current pulse.

## I. INTRODUCTION

Deep brain stimulation (DBS) has demonstrated significant therapeutic benefits [1] in (i) treating symptoms relating to neurological motor disorders including Parkinson's disease, essential tremor, and dystonia, (ii) controlling epilepsy, and (iii) providing relief from chronic pain. DBS has been also employed for treatment refractory neuropsychiatric indications including Tourette's syndrome, obsessive compulsive disorder, and for treatment resistant depression. More recently, DBS has been proposed as a potential treatment of severe drug and alcohol addiction [2].

Considerable research involving laboratory animals has been conducted in recent years to study the underlying principles of DBS and the mechanisms through which its therapeutic effects are mediated. However, a bottleneck in

establishing the therapeutic mechanisms and benefits of DBS has been the lack of portable DBS systems that enable long term brain stimulation in freely moving laboratory animals. As a consequence of this, there remains a gap in the existing experimental data investigating mechanisms of chronic DBS action in preclinical animal studies. Most of the existing DBS devices employ complex circuitry and are, as a consequence, quite bulky. These devices are connected to the implanted electrode through long insulated wires that run from the device to the animal's head. The stimulator often needs to be disconnected from the electrode over the course of the study (i.e. overnight as the animal is returned to its home cage). Thus, in order to better reflect the longer duration stimulation applied to the brain in clinical trials, the laboratory animal would ideally receive

this brain stimulation continuously without interruption for days or even weeks. In order to improve the quality of preclinical work, the animal needs to be able to freely move, eat, sleep, swim in water, and carry out several other activities. When connected to the DBS device through long wires, behavioral tests and normal behaviors are substantially limited. The progress of understanding the therapeutic mechanisms and benefits of DBS will benefit from the reduction of the size of power requirement of DBS devices.

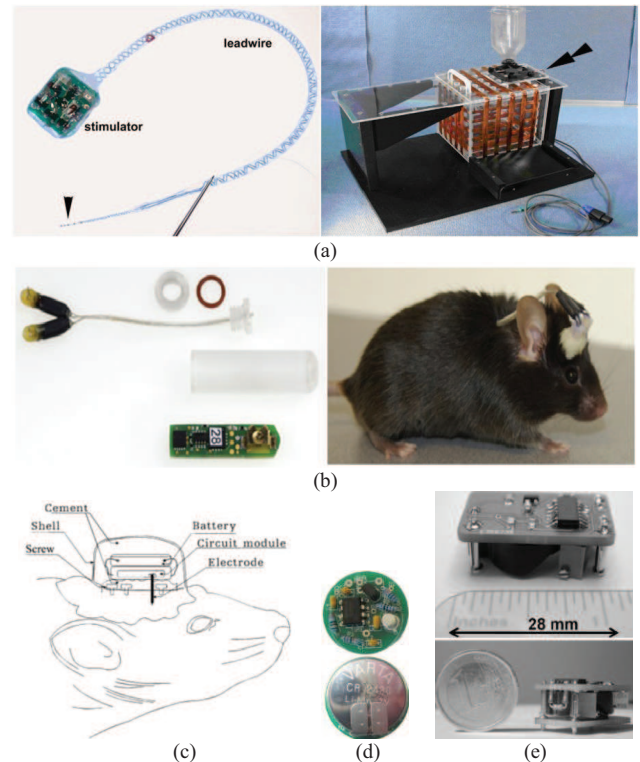
This paper presents a novel design for a low power micro deep brain stimulation device for laboratory animals. Three different configurations of the device are presented: single piece head mountable, single piece back mountable, and two piece back mountable. The device can be easily carried by the animal over the course of a study. It can produce continuous current pulses of desired characteristics.

## II. EXISTING MICRO BRAIN STIMULATION DEVICES FOR LABORATORY ANIMALS

An investigation of the literature reveals that thus far only a few DBS devices have been reported that are suitable for long term brain stimulation of laboratory animals.

Millard and Shepherd [3] developed an implantable, single channel stimulator that generates charge balanced biphasic current pulses delivered to a bipolar electrode array for chronic stimulation of neural tissue (see Fig. 1(a)). The system is magnetically coupled. The subject is placed in a small chamber surrounded by three orthogonal coils of wire which are driven to generate a magnetic field. Currents are induced in wire coils in the implanted stimulator then regulated to produce biphasic current pulses with fixed amplitude of up to  $500 \mu\text{A}$ . Phase duration is adjustable from 25 to  $250 \mu\text{s}$  per phase. Charge balance is maintained by capacitive coupling and shorting of the electrodes between pulses. Stimulus rate can be continuously varied, and the temporal precision of the stimulus means that the stimulator can be used in behavioral experiments or for generating electrically evoked potentials. The application of the stimulator on chronic electrical stimulation of the auditory nerve was described.

Haas et al. [4] developed a lightweight implantable micro stimulator device for mice that delivers biphasic pulses to two individual electrode pairs (see Fig. 1(b)). It consists of an implantable stimulator, two stimulation electrodes, an infrared camera system including a monitor and a programming and test fixture to program the stimulus current. The stimulator housing contained a polycarbonate cylinder with a screw top, and was 30 mm in length with a diameter of 8 mm. The total length of the lead system from the stimulator to the connector pins was 45 mm. The stimulator provided biphasic pulse patterns to two individual electrodes. The stimulator was battery powered and reusable. A coin magnet was used to switch the stimulator on or off. The stimulator had two modes of operation, standby mode and active mode. In active mode, the stimulator continuously generated stimulus pulse patterns. The microcontroller then had the highest power



**FIGURE 1. Micro DBS devices developed for laboratory animals by (a) Millard and Shepherd [3], (b) Haas et al. [4], (c) Liu et al. [5], (d) Kouzani et al. [6], and (e) Forni et al. [8].**

consumption of all the components of the circuit. To maximize battery life, the microcontroller was put in standby mode in between two consecutive biphasic pulse patterns. The bench top validation and *in-vivo* implementation of the device was presented. The results indicate that the wireless implantable stimulator in mice delivered continuous bilateral stimulation without restricting the animal mobility and hygiene. *In-vivo* testing showed that stimulation of the mice ventral striatum yields similar results as previously shown by others in rats where conventional deep brain stimulation techniques were used. The details of the circuitry of the stimulator were not given.

Liu et al. [5] reported a head mountable apparatus and implant method suitable for chronic DBS in rats (see Fig. 1(c)). They evaluated the effect of chronic DBS of the rat nucleus accumbens on morphine reinforcement using their DBS apparatus. An electrode was stereotaxically implanted into the core of unilateral nucleus accumbens and connected to the DBS apparatus fixed to the rat skull. The animals were administered a 130-Hz stimulation once per day. A 900-second conditioned place preference paradigm was used for determining the effect of electrical stimulation on morphine reinforcement. The details of the circuitry of the developed apparatus were not given.

Kouzani et al. [6] developed a head mountable DBS device for laboratory animals (see Fig. 1(d)). It produces continuous monophonic current pulses of  $90 \mu\text{s}$  width, with

frequency of 130 Hz, and amplitude of  $200 \mu\text{A}$ . To produce timing pulses, a general purpose timer chip was used in its astable mode. To deliver electric current pulses, a current source chip was employed. The device has passive charge balancing feature to minimize undesirable tissue damage. It was constructed on a two layer printed circuit board. The device was able to produce non-stop stimulating current pulses for about nine days using a 280 mAh coin battery. They did not carry out experiments with laboratory animals, but used a  $1 \text{ k}\Omega$  resistor to model the animal's brain tissue.

Ewing and Grace [7] reported a DBS device for the continuous delivery of brain stimulation in rats. Their device was configured to stimulate with square, monophasic, anodic, constant current 100 ms pulses at frequency of 130 Hz and amplitude of 100 mA. The device was carried by the animals via rodent jackets and connected to the electrodes via an external cable. They used the device to examine how five days of stimulation affected rhythmic brain activity in freely moving rats. Synchronized video and local field potential data was collected from animals in their home cages before, during and after stimulation. They reported that the initial changes in power observed with short term stimulation were replaced by altered coherence, which may reflect the functional action of DBS. The details of the circuitry of the DBS device were not given.

Forni et al. [8] developed a microstimulator for DBS of rats (see Fig. 1(e)). This device can be clipped to a support fixed on the animal's head. This easy removal property enables removing or switching the microstimulator during the experiments without having to anaesthetize or operate on the animal, thereby minimizing stress, and maximising the quality of the behavioural and biological data. The DBS system consists of three components: a stimulating electrode, a stimulator support and an electrical portable microstimulator. The microstimulator is made up of two main blocks: one adjustable pulse generator and one voltage to current converter. The pulse generator block is based on a series of four CMOS inverters' chains with a feedback loop allowing to regulate the frequency and a buffer stage on the two last ones, both being coupled through a variable network allowing to vary the duty cycle. The voltage to current converter is based on a classical bipolar transistor Wilson current mirror directly supplied by the buffer output to minimize consumption during off phases of the pulse. The power supply consists of two 3 V lithium watch batteries connected in series. The microcircuit is coated with a polyurethane resin. Its weight is around 5.6 g with the resin protective coat, and 7.4 g with the two watch batteries. The initial setting of the current parameters is done before mounting the microstimulator on the head of the rat using an oscilloscope and a  $15 \text{ k}\Omega$  output reference resistance. To validate the device, they performed continuous DBS of the subthalamic nucleus in a classical rat model of PD. They showed that the long duration stimulation reduces significantly PD-induced akinesia without inducing animal discomfort and tissue damage.

The shortcomings of the current devices are as follows. The Millard and Shepherd's device [3] requires a magnetic field that is generated by applying a high voltage to the excitation coil which may have undesirable impact on biological cells. The animal needs to be kept in a small chamber. The Haas et al.'s device [4] requires new data to be uploaded to the microcontroller and some fixed resistors be changed for changing the characteristics of the stimulation current. The size of the device is large, and the device can only stimulate for several hours. The Liu et al.'s device [5] does not describe about charge balancing of the stimulation pulses. In addition, the weight of the device is not stated. The Kouzani et al.'s device [6] uses a large battery, and hence has a large size. The stimulation parameters cannot be adjusted. The device can operate for nine days. The Forni et al.'s device [8] requires an extra support to place stimulator on the rat head. The stimulus parameters are varied manually by varying the hardware circuit components. The size of the device is large. The device can operate for seven days. The cost of these devices is not reported in their associated publications. Considering the characteristics of the current devices, there is still a need to reduce their power consumption, size, weight, cost, and simplify their maintenance and mounting procedures.

### III. PROPOSED MICRO BRAIN STIMULATION DEVICE

A low power, lightweight portable micro DBS device that can be carried by the animal during the course of a clinical trial is presented in this section. The device produces continuous monophasic current pulses. Based on our preclinical research requirements, the duration of the cathodic pulse is set to  $90 \mu\text{s}$ , the frequency of stimulation is set to 130 Hz, and the amplitude of current pulses is set to  $200 \mu\text{A}$ . However, the stimulation parameters of the device are adjustable as described in the programming subsection.

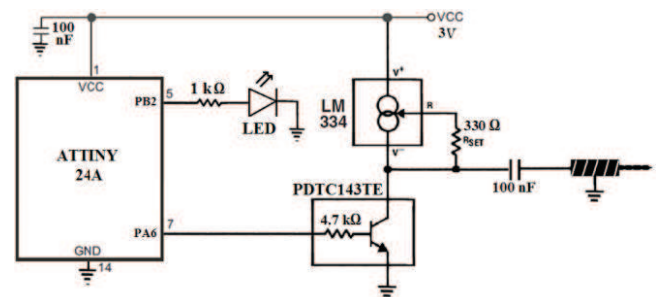


FIGURE 2. Schematic circuit diagram of the micro DBS device.

The device employs the passive charge balancing method to minimize undesirable effects including tissue damage. The passive charge balancing method is based on an ac-coupling capacitor reducing the demanding electronic circuit. Fig. 2 illustrates the schematic circuit diagram of the micro DBS device. The device consists of the following components: microcontroller, current source, stimulation electrode, power source, and printed circuit board.

Three different configurations of the micro DBS device are constructed: single piece head mountable, single piece back mountable, and two piece back mountable. The three configurations share the circuit shown in Fig. 2.

### A. MICROCONTROLLER

ATtiny 24A is a low power 8-bit microcontroller based on the AVR enhanced reduced instruction set computing architecture [9]. It offers throughputs near 1 MIPS per MHz. It provides 2 KB of flash, 128 bytes of EEPROM and SRAM, 12 I/O lines, 32 registers, an 8-bit timer/counter, a 16-bit timer/counter, internal and external interrupts, 8-channel 10-bit ADC, a programmable watchdog timer, and internal calibrated oscillator. It is an ideal microcontroller for low power applications. It offers four selectable power saving modes: (i) in idle mode, the CPU is stopped while allowing the SRAM, timer/counter, ADC, analog comparator, and interrupt system to continue functioning, (ii) in ADC noise reduction mode, switching noise during ADC conversions is minimized by stopping the CPU and all I/O modules except the ADC, (iii) in power down mode, registers keep their contents and all chip functions are disabled until the next interrupt or hardware reset, (iv) in standby mode, the crystal/resonator oscillator is running while the rest of the device is sleeping, allowing very fast start up combined with low power consumption.

### B. PROGRAMMING

The microcontroller is programmed in C programming language. The pseudo code for the program that implements the deep brain stimulation operation is given in Fig. 3. The program involves five steps as described in the following.

<p><b>Begin</b></p> <ol style="list-style-type: none"> <li>1. Set data direction for output port pins.</li> <li>2. Set power reduction by disabling unnecessary peripheral clock signals.</li> <li>3. Flash the LED several times.</li> <li>4. Program Timer 1 in fast pulse width modulation mode 14.</li> <li>5. Make the microcontroller enter the idle mode.</li> </ol> <p><b>End</b></p>
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**FIGURE 3. Pseudo code for the program that implements the deep brain stimulation operation.**

In the first step, data direction for output port pins is set. This is done by initializing the two data direction registers of the microcontrollers, DDRA and DDRB. The OC1A and PB2 pins of the microcontroller are set as output pins. The other I/O pins are configured as input pins.

In the second step, power reduction is enabled by disabling unnecessary peripheral clock signals. This is achieved by initializing the power reduction register, PRR.

In the third step, the LED is flashed to show the user that the device has started and is operating correctly, and that the battery is in good condition.

In the fourth step, the 16-bit Timer/Counter 1 unit is programmed to generate the stimulation waveform. The unit

facilitates precise event management, wave generation, as well as signal timing measurement. It has a number of control registers that can be programmed to determine the desired operation of the unit. In this work, the unit is programmed to act as a free running timer. The timer is clocked internally with the frequency of 1 MHz. The timer can be programmed to operate in 15 different waveform generation modes. In this work, the timer is operated in fast pulse width modulation (PWM) mode 14. The fast PWM mode has a single-slope operation. It counts from a bottom value to a top value then restarts from the bottom value. For generating a stimulation waveform of width 90  $\mu$ s, and frequency 130 Hz, the ICR1 and OCR1A registers are set to 7692 and 90, respectively. However, by varying the content of the timer control registers, the characteristics of the generated waveform can be changed, resulting in the adjustment of the stimulation parameters.

Finally, in the fifth step, for power efficiency and to maximize the battery lifetime, the microcontroller is made to enter the idle mode. In this mode, all unused modules in the microcontroller are shut down, thereby saving power. Accordingly, the CPU and the execution of the program is halted and no further instruction is run, but Timer 1 continues operating to provide the desired waveform on its output pin without the intervention of the CPU. The produced waveform is used to switch on/off the transistor PDM143TE that controls the operation of a current source.

### C. CURRENT SOURCE

To deliver electric current pulses, a current source chip is employed. LM334 is an adjustable current source with good current regulation from 1  $\mu$ A to 10 mA under a voltage range of 1 V to 40 V. The device has three terminals and offers true floating current feature. The current amplitude  $I_{SET}$  is determined by an external resistor  $R_{SET}$  as follows [10]:  $I_{SET} = (1.059 \times V_R)/R_{SET}$ , where  $V_R$  is the voltage across  $R_{SET}$ . The average  $V_R$  for the desired operating temperature range is about 62 to 66 mV. For the current amplitude of 200  $\mu$ A, we therefore used  $R_{SET} = 330 \Omega$ .

### D. STIMULATION ELECTRODE

To achieve charge injection, the stimulation electrode is implanted into the target tissue. A variety of electrodes exists that can be used for charge injection. They have different electrochemical properties and shapes. We used an electrode by PlasticsOne that has a stainless steel twisted wire electrode extend below a threaded plastic pedestal. The threaded plastic pedestal accepts the captive collar of a plug. The pedestal is secured with Cerebond or dental cement and mounting screws.

### E. POWER SOURCE

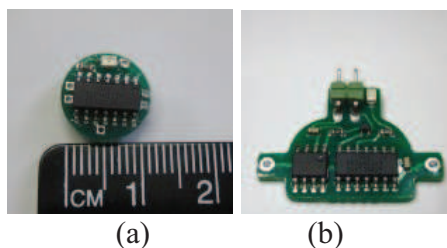
To supply energy to the micro DBS device for the duration of a clinical trial, a battery is used. For the single piece head mountable configuration, two cell button silver oxide 1.55 V batteries are used to power the device. The diameter and the height of each battery are 11.6 mm and 5.4 mm, respectively.

The weight of the battery is 2.3 g. The capacity of each battery is 190 mAh which is well adequate for operating the device for about ten days. The two batteries are stacked together using conductive glue to form a 3.1 V source.

For the single piece back mountable and the two piece back mountable configurations, one cell button lithium manganese dioxide 3 V battery is used to power the device. The diameter and the height of the battery are 20 mm and 3.2 mm, respectively. The total weight of the battery is 2.8 g. The capacity of the battery is 235 mAh which is also well adequate for operating the device for over eleven days.

#### F. PRINTED CIRCUIT BOARD

To accommodate the components of the micro DBS device, and connect them according to the circuit schematic shown in Fig. 2, two printed circuit boards are developed, one for the single piece head mountable as well as the two piece back mountable configurations, and another for the single piece back mountable configuration. After fabrication of the printed circuit board, the electronic components of the micro DBS device are assembled onto the boards. Fig. 4 shows samples of the two assembled boards.



**FIGURE 4.** Fabricated boards. (a) The board for the single piece head mountable as well as the two piece back mountable configurations. (b) The board for the single piece back mountable configuration.

#### G. SINGLE PIECE HEAD MOUNTABLE CONFIGURATION

This configuration incorporates both the stimulation board and the battery pack as a single piece device that can be attached directly into the stimulation electrode implanted into the target tissue. The board includes a two pin terminal for connection to the positive and negative sides of the battery pack, and another two pin terminal for connection to the electrode. A thin brass sheet is cut into small pieces and attached to the positive and negative sides of the battery pack using conductive glue. The battery pack is placed under the stimulation board. Then, the power terminals are soldered onto the brass pieces on the positive and negative sides of the battery pack. A sample of the single piece head mountable micro DBS device is shown in Fig. 5.

The weight of different components of different components of the single piece head mountable micro DBS device is measured using a laboratory scale. The weight of the stimulation board is 0.71 g, the weight the battery is 2.56 g, and the weight of the entire device is 3.27 g. During the implant procedure, the threaded plastic pedestal of the electrode is fixed into the skull. Next, the stimulation device including the



**FIGURE 5.** Sample of the single piece head mountable micro DBS device.

battery is mounted into the electrode via the two pin electrode terminal on the device. Then, the device is sealed with dental cement on top of the animal's head.

#### H. SINGLE PIECE BACK MOUNTABLE CONFIGURATION

This configuration incorporates the stimulation board, a 20 mm cell button battery holder, and the cell button lithium manganese dioxide 3 V battery in a single piece device. The stimulation board is secured underneath the battery holder. The board includes a two pin 2.54 mm terminal for connection to the electrode. A two way 2.54 mm receptacle is used to plug a pair of thin wires into the electrode terminal of the stimulation device. The other end of the wires is connected to a two pin plug that is mounted into the electrode fixed into the skull. The wires are placed under the animal skin. The cell button lithium manganese dioxide 3 V battery is placed inside the battery holder. The whole device is placed in a rat jacket. The jacket is closed by using a velcro fastener, and a hook gives a secure fit. The jacket is then mounted on the back of the animal. This arrangement allows the battery to be easily replaced. The advantage of this configuration is the fact that the battery can be easily replaced extending the operation time of the device unlimitedly. Fig. 6 shows samples of the single piece back mountable micro DBS device.



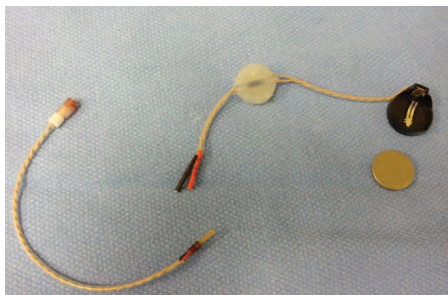
**FIGURE 6.** Sample of the single piece back mountable micro DBS device.

The weight of different components of different components of the single piece back mountable micro DBS device

is measured using a laboratory scale. The weight of the stimulation board is 1.25 g, the weight of the battery is 2.83 g, the total weight the battery and the battery holder is 3.83 g, and the overall weight of the entire device is 5.08 g.

### I. TWO PIECE BACK MOUNTABLE CONFIGURATION

This configuration is similar to the single piece back mountable formation. The difference is that in this configuration the stimulation board and the battery-holder/battery are separate. The stimulation board is connected to the battery holder using a pair of thin wires instead of being secured underneath the battery holder. Similarly, the board includes a two pin terminal for connection to the electrode. A pair of thin wires connects the stimulation device to the electrode. A second pair of wires connects the stimulation device to the battery holder. The wires are placed under the animal skin. The battery holder and the battery are placed in a rat jacket. The jacket is then mounted on the back of the animal. The stimulation device can be sealed using hot glue and then placed under the animal skin. Alternatively, it can be placed inside the rat jacket near the battery holder. A sample of the two piece back mountable device is shown in Fig. 7. The overall weight of the device is similar to that of the single piece back mountable device which is around 5.1 g.



**FIGURE 7.** Sample of the two piece back mountable micro DBS device.

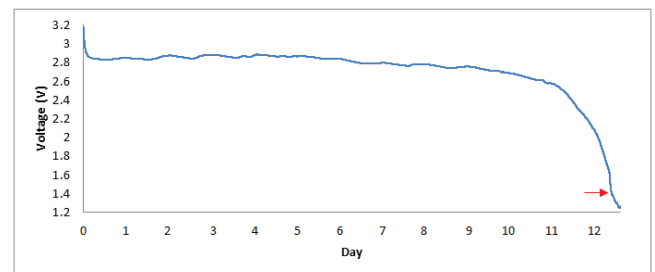
### IV. EVALUATION

After construction of the micro DBS devices, their performance was evaluated in terms of the lifetime of the battery and also the operation of the device. Three tests were conducted: bench test, *in-vitro* test, and *in-vivo* test.

#### A. BENCH TEST

The performance of the micro DBS was tested using a 1 k $\Omega$  resistor that modeled the animal's brain tissue. The device was tested using the 235 mAh cell button battery. The bench testing of the micro DBS device with a 1 k $\Omega$  resistor. The steady state current consumption of the device after 10, 20, and 30 hours of continuous operation was measured using a Keithley 2401 SourceMeter. The SourceMeter has precision current measurement capability within the range 10 pA–1 A. The average steady state current consumption of the device was found to be around 870  $\mu$ A. Next, to practically determine the number of days the device can be operated by

using the 235 mAh cell button battery, the SourceMeter was programmed to read the battery voltage and store it every five minutes. The collection of the data was carried out at non-regulated room temperature. The variation of the battery voltage for the continuous operation of the micro DBS device using a 235 mAh cell button battery is shown in Fig. 8. As can be seen from the figure, the battery voltage remained steady over the course of the first eleven days. It then started declining from around the 2.7 V mark. Theoretically, the operating voltage of the ATtiny 24A microcontroller is within the range 1.8–5.5 V. However, the system continued producing stimulating current pulses below 1.8 V in day 12. Once the battery voltage fell below 1.5 V, the microcontroller stopped working, and thus the device stopped producing the stimulation pulses. The red arrow in Fig. 8 shows when the device ceased operation due to the low battery voltage after over twelve days of continuous operation. Overall, the device produced the stimulation pulses for about 12.3 days.



**FIGURE 8.** Variation of the battery voltage under continuous operation of the micro DBS device using a 235 mAh cell button battery.

A comparison of the head-mountable configuration against similar current devices is presented in Table I. In comparison of the lifetime of each device, the strength of the stimulation current as well as the use of an external source should be taken into account. The head-mountable configuration offers a much smaller size, and yet longer term higher strength stimulation current pulses.

#### B. IN-VITRO TEST

The micro DBS device was tested *in-vitro* at Mayo Clinic by Dr Abulseoud's team. The test was conducted by placing the stainless steel twisted wire part of the stimulation into a tank of physiologic saline solution. The cathodic pulses of 90  $\mu$ s duration, 130 Hz frequency, and 200  $\mu$ A amplitude were delivered to the electrode by the device which was powered by the 235 mAh cell button battery. An oscilloscope was used to confirm the continuous delivery of current to the stimulating electrode. The device functioned successfully for over twelve days on a single battery.

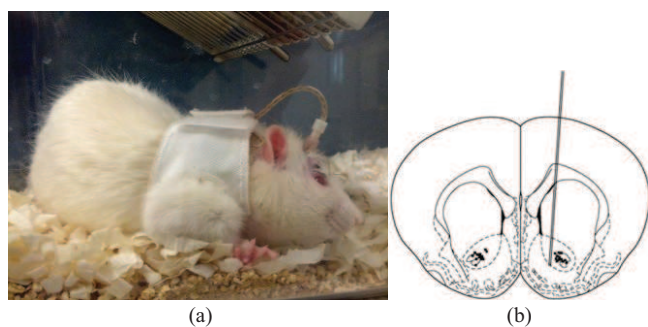
#### C. IN-VIVO TEST

After the successful bench test and *in-vitro* test, a number of two piece back mountable micro DBS devices (see Fig. 7) were tested *in-vivo* at Mayo Clinic by Dr Abulseoud's group. The devices were used in a study to examine the role of

**TABLE I. Comparison of micro DBS devices.**

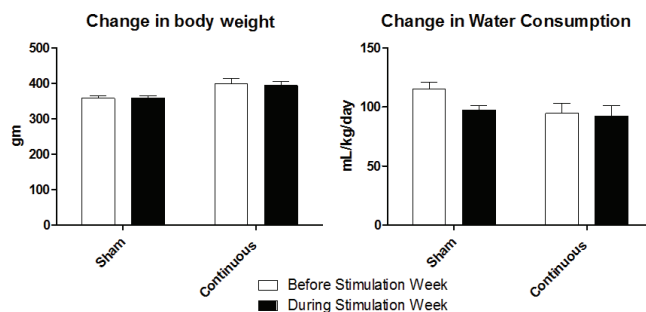
Ref.	Size	Source	Weight	Term	Parameters
[3]	14mm × 12mm	Magnetic coupling	2.5g	Un-limited	100-500μA 25-250μs 50-5000Hz
[4]	8mm × 30mm	Battery (4.65V)	2.1g	10 hours	20-100μA 60μs 131Hz
[5]	20mm diameter	Battery (3V/ 200mAh)	-	-	0.2-0.5mA 0.03-1.4ms 1-200Hz
[6]	25mm diameter	Battery (3V/ 280mAh)	7.8g	9 days	200μA 90μs 130Hz
[8]	15mm × 28mm	Battery (6V/ 36mAh)	7.4g	7 days	50-120μA 0-80μs 0-130Hz
Proposed	12mm diameter	Battery (3.1V/ 190mAh)	3.2g	10 days	200μA 90μs 130Hz

DBS in reducing ethanol preference in alcohol preferring rats. Eleven adult male Wistar rats (Charles Rivers) 12-16 weeks at time of experiment were used. A pair of thin wires connected the stimulation board to the electrode. A second pair of wires connected the stimulation board to the battery holder. Each device created pulses of 90 μs duration, 130 Hz frequency, and 200 μA amplitude whilst being powered by a 235 mAh cell button battery. The stimulation board, the battery holder and the battery were all placed in a rat jacket (Harvard Apparatus) and secured on the back of the animal. The pair of wires connecting the stimulation board to the stimulating electrode was tunneled under the skin at the back of the neck and externalized for a short distance above the stimulating electrode where it was connected (see Fig. 9(a)). The animals did not appear to be bothered by the device, the jacket, or the wires.



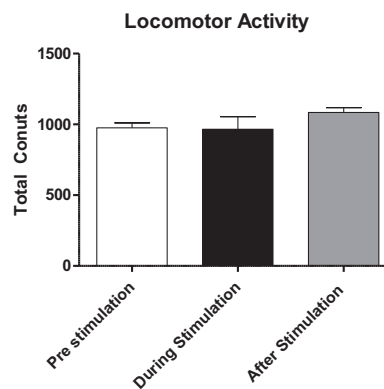
**FIGURE 9. (a) Testing the micro DBS device in-vivo. (b) Location of the implanted electrode.**

Animals were implanted with bipolar twisted electrode (PlasticsOne) into the right Nucleus accumbens shell under isoflurane inhalation anesthesia (3.0% during induction and



**FIGURE 10. Body weight and water consumption of the animals before stimulation week and during stimulation week.**

1.5% during maintenance) (see Fig. 9(b)). Coordinates from Bregma (Flat skull) are: AP = 2.04, M-L = 1.2, D-V = 8.0 (from skull) Tilt: 10 degrees. Animals were allowed to recover for three days post-surgery then were divided into two groups: continuous stimulation for 7 days using the head mounted device in a jacket (n = 5) and sham group did not receive stimulation (n = 6). Data on body weight and water consumption as well as locomotor activity counts was collected during the week before stimulation and during the week of stimulation (for the continuous group). The weight and water consumption of animals are shown in Fig. 10. As can be seen from the figure, the sham group had less weight at start of experiment, but no significant effect for stimulation on weight as well as total water consumption was found (two-way ANOVA).



**FIGURE 11. Locomotor activity of the animals.**

Animals (n = 5) were housed under 12:12 hour dark: light cycle (lights on at 6.00 AM) Circadian locomotor activity counts in home cage were recorded using an infrared motion detector interfaced with a computerized data acquisition system (Clocklab) and later analyzed using Matlab software. No significant difference in total locomotor activity counts pre, during, or after stimulation was observed (one way repeated measure ANOVA p = 0.2) (see Fig. 11). The stimulating device was well tolerated and the stimulation at the NAC did not alter weight, water consumption or locomotor activity, however it resulted in changes in alcohol consumption and

preference in alcohol preferring rats (data not shown here, and will be published by Dr. Abulseoud's group).

## V. CONCLUSION

The paper presented the development and testing of a low power lightweight micro deep brain stimulation device for laboratory animals. Three configurations of the device were presented. The device is both head mountable and back mountable. It can be easily carried by the animal during the course of a clinical trial. It produces continuous current pulses of desired characteristics. It was constructed on a two layer printed circuit board. After construction, the performance of the device was evaluated through three tests: bench test, *in-vitro* test, and *in-vivo* test. During the tests, the device was able to produce non-stop stimulating current pulses for over twelve days using a 235 mAh cell button battery. The evaluation of the device in a study to examine the role of DBS in reducing ethanol preference in alcohol preferring rats was successful. Whilst it did not alter weight, water consumption or locomotor activity of the animals, it resulted in changes in alcohol consumption and preference in alcohol preferring rats. In order to minimize the power consumption, size, and weight of the device, the recording of local field potentials has not been included in this device. However, such feature can be implemented by incorporating a recording electrode and a signal conditioning interface circuit. The microcontroller used in the device has 10-bit analog-to-digital converter channels that can be used to convert the conditioned output of the recording electrode to a high resolution digital signal. In addition, similar to the current stimulation devices involving any stimulation electrode, wire, and/or electronic component, performing MRI/fMRI with this device can also cause tissue damage from component heating particularly around the electrode. The advantages offered by the device include: (i) ultra-low cost when mass produced. It is expected that the entire device will cost less than \$5; (ii) ultra-low maintenance and ease of use; (iii) quick and easy battery replacement enabling ultra-long term stimulation.

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**ABBAS Z. KOUZANI** (M'95) received the B.Sc. degree in computer engineering from Sharif University of Technology, Tehran, Iran, in 1990, the M.Eng. degree in electrical and electronics engineering from the University of Adelaide, Adelaide, Australia, in 1995, and the Ph.D. degree in electrical and electronics engineering from Flinders University, Australia, in 1999. He was a Lecturer with the School of Engineering, Deakin University, Victoria, Australia, and a Senior Lecturer with the School of Electrical Engineering and Computer Science, University of Newcastle, Newcastle, Australia. Currently, he is an Associate Professor with the School of Engineering, Deakin University. He has been involved in over 1.9 million research grants, and he has published over 200 refereed papers. He served as the Associate Head of School (Research) with the School of Engineering, Deakin University, for several years. He is an OzReader with the Australian Research Council, and reviews for a number of international journals and conferences. He has carried out applied research and consultancy for several Australian and international companies. His current research interests include medical/biological microdevices, lab-on-a-chip systems, bioinstrumentation, and biosensors and implants. He is the Leader of Deakin University's BioMEMS Group.



**OSAMA A. ABULSEOD** received the M.D. degree from Cairo University, Cairo, Egypt, in 1991, the M.Sc. degree in general surgery and the Diploma degree in internal medicine from Aim Shams University, Egypt, in 1996 and 1997, respectively. He received training in General Adult Psychiatry with the University of Southern California, Los Angeles, CA, USA, and a Post-Doctoral Fellowships in mood disorder research with the University of California Los Angeles, a Brain Imaging Research with Huntington Medical Research Institute, CA, USA, and an Addiction Psychiatry with Mayo Clinic. He is a Board Certified in general psychiatry, psychosomatic medicine and addiction psychiatry. He is an Assistant Professor of psychiatry with Mayo Medical School, with clinical practice in mood disorders and teaching activities in psychopharmacology. He received a Career Development Award (KL2) to study the effect of nucleus accumbens deep brain stimulation on alcohol consumption in a preclinical model in 2011. He is involved in basic, clinical, and translational research with a focus on studying the disease process and novel therapeutic strategies. He has published 22 papers in peer-reviewed journals. He is a member of the Society of Biological Psychiatry, the International Society of Bipolar Disorder, and the Research Society of Alcoholism.





**SUSANNAH J. TYE** received the Ph.D. degree from the Departments of Psychology and Biological Sciences, Macquarie University, in 2008. She received the Post-Doctoral Fellowship with the Department of Neurosurgery, Mayo Clinic, USA. Currently, she is an Assistant Professor of psychiatry and psychology, where she directs the Translational Neuroscience Laboratory, with a focus on developing valid preclinical models of treatment resistant depression and bipolar disorder for investigation of disease and therapeutic mechanisms, utilizing deep brain stimulation. She received a number of grants and awards, including the 2013 NCDEU New Investigator Award, the Mayo/Minnesota Partnership Grant in 2012, the Sir Winston Churchill Fellowship from 2010 to 2011, and the National Alliance for Research on Schizophrenia and Depression (NARSAD) Young Investigator Award in 2009. She co-supervises four post-graduate students, two research technicians, and one research fellow. She is a member of the Society for Neuroscience, Society of Biological Psychiatry and the International Society of Bipolar Disorder. She has provided a number of community outreach presentations in Australia and the U.S., where she continues to work with researchers and health psychology professionals to develop school-based mental illness awareness and prevention programs.



**MD KAMAL HOSAIN** (S'12) was born in Bangladesh in 1984. He received the B.Sc. Engineering degree from the Khulna University of Engineering & Technology, in 2001, and he was a Lecturer with the Department of Electronics and Telecommunication Engineering, Rajshahi University of Engineering & Technology, Bangladesh. Currently, he is pursuing the Ph.D. degree with Deakin University, Victoria, Australia. His current research interests include development of devices, and antennas and their applications to biomedical engineering, particularly brain stimulation.



**MICHAEL BERK** is the Foundation Chair in psychiatry with Deakin University, Victoria, Australia. He leads the Barwon Psychiatric Research Unit as well as the Professorial Unit with The Geelong Clinic. He is a Professorial Research Fellow with the University of Melbourne, Melbourne, Australia, and the Mental Health Research Institute, and leads the First Episode Bipolar Program with Orygen Youth Health. His current research interests include mood disorders, particularly bipolar disorder. His research focuses on biomarkers of risk for psychiatric disorders, particularly oxidative and inflammatory, and the modulation of these in the development of novel therapies, and on lifestyle and medical determinants of outcome in high prevalence psychiatric disorders. His projects include internet therapies, drug safety, biomarkers, and early intervention.