Early steps toward the development of a wireless neurostimulator powered and controlled by radio waves

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Brain-machine interfaces communicate data from the brain to external devices to monitor patient health during procedures, such as deep brain stimulation for Parkinson's disease and in medical research. The lack of safe and long lasting implantable devices hampers the improvement of brain-machine interfaces and deep brain stimulation for research and patient therapies. In this paper, we describe the first steps towards a wirelessly-powered and controlled neural and motor tissue stimulator. We constructed a wireless, external-stimulation device using a tank circuit and stimulation leads. We quantified the relationship between radio-frequency (RF) source-distance and strength-of-voltage-output to determine if the stimulator was powered and controlled by Ultra High Frequency (UHF) and far-field coupling or Very High Frequency (VHF) and near-field coupling. We then implanted the stimulation leads in a cricket leg and tracked the physical motion of a cricket leg in response to stimulation from the device. Our findings suggest the device used VHF to induce near-field inductive coupling to power the circuit and stimulate excitable tissue. Given that our device is powered by VHF waves, the stimulator requires relatively large antennas, which limit the miniaturization of the device. Additionally, VHF waves power and control the voltage emitted from all stimulation leads connected to one device. This prohibits emission of different voltages from different stimulations leads. The lack of voltage specificity hinders clinical and research uses. Future studies should further the miniaturizing of the device, creating a frequency discriminatory system to stimulate one stimulation lead at a consistent determinable voltage, and determining the efficacy of VHF transmission through biological tissue.

Abbreviations: BMI – Brain Machine Interfaces; RF – Radio Frequency; UHF – Ultra High Frequency; VHF – Very High Frequency

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Introduction

Limits to the development of implantable brain-machine interfaces (BMI), devices that transmit data from the brain to external devices and neurostimulators, include numerous replacement surgeries, large sizes, excessive heat, and risk of infection due to the wires that are associated with batter-powered implantable devices. Many battery powered implantable medical devices use neurostimulation to deliver therapeutic stimulation for Parkinson's Disease, depression, and other conditions (Anderson et al., 2006; Grisaru et al., 1994; Perlmutter et al., 2006). However, these battery-powered implantable devices require additional surgeries after implanting the device to replace the battery when its charge runs low. Long-life batteries are so large and generate such unsafe levels of heat in heat-sensitive tissues that surgeons cannot implant the batteries at the site of the stimulus. Given a battery's size and heat, the battery may be distantly located from the device and connected by long wires. Wires pose a risk for infection and patients may displace the wires during quotidian movement. In a research setting, wires can also reduce a model organism's mobility and its expression of species-specific behaviors (Arfin et al., 2009).

Connection sites for wires require charging ports, battery compartment doors, and other irregular surfaces. Devices with irregular surfaces are difficult to sterilize and more prone to failure than smooth medical devices. In order to further the development of implantable brain-machine interfaces, and subsequent neurostimulation treatment for Parkinson's Disease, depression, and other conditions, scientists must create a more suitable power source for implantable devices (Seo et al., 2013).

Wirelessly transmitting power to an implanted device would further the development of a brain-machine interface that remains viable throughout an organism's lifetime. Papale et al (2012) proposed an implantable sensing device that would be physically uncoupled from its power source and would wirelessly transmit electrochemical, acoustic, and optical data to a receiver for analysis by a clinician or researcher. This device would receive power transmitted through body tissues and fluids from a physically-uncoupled power source within several meters of the device. The tissues and fluids of the bodies would serve as natural, conductive pathways that would electrically connect the power source and the device. A distant power source that transmits radio waves through the body, like Papale's proposed device, would allow scientists to miniaturize stimulation devices, remove long wires, and implant a device closer to the stimulation target site.

In the event that tissue does not contain enough fluid to serve as a natural conductive pathway, scientists can use inductive coupling to transfer energy. There are many commercial uses of inductive coupling to transfer power between devices, such as electric toothbrushes and mobile phone charging stands. Inductive coupling transmits electric potential to power a physically-uncoupled device in the near field, the area proximal to the antenna, and far field, the area farther than either the wavelength of the frequency or the greatest physical dimension of the antenna. Radio antennas radiate energy receivable as alternating current in both the near field and far field. For example, many passive Radio Frequency Identification tags are powered by near-field radiation, whereas shortwave radio transmitters use far-field radiation to transmit signals all over the world. VHF radio waves (30 to 300 MHz) power near-field waves that transfer electric potential less than one wavelength from the radio-frequency (RF) source. In contrast, UHF radio waves (300MHz to 3 GHz) power far-field waves to transfer electric potential more than one wavelength away from the RF source. Near-field and far-field wireless inductive coupling safely powers affordable innovations already on the market.

Transcutaneous inductive coupling successfully transmits power to and collects data from devices using a single pair of coils, which cost-effectively eliminates batteries (Hussnain et al., 2009). Waters et al. (2012) proposed the development of a Left Ventricular Assist Device (LVAD) that would improve circulatory function of a weakened heart using inductive coupling to recharge batteries. The device was not constructed or tested in an organism. The power supply would be physically coupled to the device, but recharging of the power supply would occur without wires or battery compartment between the implanted, rechargeable power supply and the external charger. Devices powered by inductive coupling may be scaled to an appropriate size and designed to be smooth, non-hostile to neurological tissue, and more controlled to deliver stimulation.

In this study we wirelessly powered and controlled an implantable neurological stimulator to begin development of a miniature, smooth wireless stimulation device powered by inductive coupling. This device could eventually stimulate tissue without carrying the same risk of infection, size and heat barriers of existing devices. We recorded the voltage produced by the stimulators in respect to distance between the stimulator and RF source to determine if the device was powered by near field or far field inductive coupling. We used the inductive coupling field to deduce if the device used VHF or UHF waves for power. We hypothesize that stimulators would produce 50 V of power at 0 cm distance between the VHF RF source and the device, and that near-field inductive coupling would power the stimulation device.

Material and Methods

Designing and Building the Device

We designed our device to be powered by a small, portable, economic battery-powered RF source and easily covered in non-toxic resin coating. To design the circuit we read descriptions of several successful insect devices and basic tank circuits to design our radio wave receiver and stimulation device (Bilkey et al., 1999; Bozkurt et al., 2009; Korivi et al., 2011; Zhang et al., 2011).

To build the circuit we used the Toolkit for Interactive Network Analysis (Budapest, Hungary, TINA). We built through-hole models using a breadboard, through-hole elements, Solomon SL-30 soldering gun and 60/40 rosin core solder. The receiving antenna was made from 9 cm of .05 mm silver wire and coiled into a 1 cm diameter coil, which was 5 cm in height. The two antennas were connected across the 1 pF capacitor in parallel with a 1 uH inductor to create a tank circuit. Due to its design, the tank circuit resonated at a frequency near our VHF signal of 159.16 MHz. It had a Quality Factor (Q) of 100, which means that wave oscillations dampened quickly and permitted UHF frequency to perform as well as or better than VHF with our device. Alternating current from the RF source was rectified to a direct current by a full-wave rectifier. The direct current generates a voltage across two stimulation electrodes.

The RF source was generated using a BaoFang BF-FH8P (Foscam Digital Technologies, LLC; Austin, TX) handheld transceiver. The RF source broadcasted the stimulus signal using a stock rubber ducky antenna, which is a common 15 cm long vertical antenna. We first used the common Multi-Use Family Radio Service frequency of 151.82 MHz (up to 2 Watts) to determine if the device could produce a voltage output. We used 151.82 MHz because it is an amateur-accessible frequency and our device was built to resonate near 151 MHz. If the device was capable of producing a voltage output, it would do so at 151.82 MHz because this frequency is so close to the resonant frequency. We set the transceiver to a VHF and UHF frequency of 446 MHz when used by a licensed amateur radio operator (up to 8 Watts) to determine if near-field or far-field inductive coupling powers the device. It was necessary to determine the inductive-coupling power source after construction because the device design and construction are compatible with both near-field and far-field induction. 446 MHz was chosen to identify the inductive coupling field because of the difference in position of origin and radius of the near- and far-fields at this frequency.

We used a Fluke 26 III True RMS Multimeter (Longbranch, NJ, TEquipment) to test the voltage of the stimulator device. The multimeter has an input impedance of 10 MΩ. The multimeter was connected across the stimulation leads to measure voltage output. The RF source was broadcast at increasing distances from the device.

Testing the Device

To determine if the RF source used near-field or far-field waves to power and control the device we connected the device to the multimeter and broadcasted signal at 446 MHZ with the RF source antenna touching the device. We then increased the distance between the RF source and device while recording the voltage output generated by the device on a multimeter. We stopped recording the voltage output at 120 cm between the RF source and device because the device no longer produced significant voltage output. The linear decay of the voltage output trend to determine power source did not lend itself to statistical analysis.

To test the ability of our device to stimulate neuromuscular contraction, we attempted to stimulate the cerci ganglia of *Archeta domesticus*. Crickets served as an ideal model insect because of the low cost and ease of acquisition, as well as the similarity between human and cricket nervous systems and well-documented surgical techniques (Dagda et al., 2013; Moore et al., 1998). The crickets were purchased from a local pet store, where they were sold as food for animals. Approximately 30 male and female adult crickets were used, one at a time, over the course of this study. The first five crickets were used in amputation and device insertion practice, five died of natural causes, and 20 crickets were used in 20 experiments. After a cricket was anesthetized on ice for about two minutes the hind legs were amputated at the coxa for testing according to Oakley and Schager's amputation standards (1978). The cricket was killed while anesthetized after the leg amputation. The leg was placed on a corkboard and the stimulation leads were placed across the leg with the positive lead near through the coxa and the negative reference lead through the femur. Multimeter alligator clamps were attached to the stimulation leads to measure the voltage output during stimulation. We triggered the stimulus signal from the RF source every 10 seconds to allow the cricket leg to return to the original position and remain still for at least 9 seconds to recover from stimulation. Cricket legs were not stimulated more than three times to eliminate sensory adaptation. We held the RF source from a distance of approximately 16 cm above the device because the receiver device demonstrated a strong electric potential of 44 V at 16 cm. We ran the final experiment without the multimeter to eliminate any interfering effect due to outside connections. We collected cricket stimulus response data by continuously recording the cricket leg position before, during, and after the stimulus on a 1080p HD iPhone 5® video camera positioned approximately 16 cm above the leg. We then analyzed the cricket stimulus response data using Kinovea Video Capturing Software (Kinovea Org; Paris, France) to slow the individual motions within the compound movement and track the position of the joint. Finally, we recorded the time of the video that each contraction took place and extracted the time corresponding still image. We used this cricket leg position data to identify the individual movements and time-to-contract within the compound motion. The cricket leg range of motion observation did not lend itself to statistical analysis.

Results

The stimulation device produced a maximum voltage output of approximately 50 V at 0 cm from the RF source. The device's voltage output decreased as the distance between the RF source and device increased to 120 cm in a manner consistent with near-field radiation coupling. The recorded voltage output decreased continuously as the distance between antenna and device increased until there was no significant voltage recorded at 70 cm between the RF source and the device. Significant recorded voltage is defined as greater than 10 mV because the cricket leg contraction is negligible when the voltage is less than 10 mV.

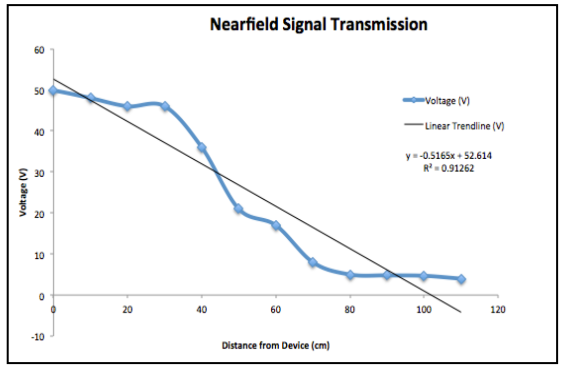

Figure 1: The voltage output from the device linearly decreases as the distance between the RF source and the device increases.

The 70 cm distance between the RF source and device is the maximum distance that near-field inductive coupling powers the device. The device can generate an insignificant voltage after 70 cm using far-field inductive coupling using UHF waves after 70 cm between the device and the RF source (Fig. 1).

The RF source distance versus voltage data closely correlate to the linear decay trend line y= -0.5165x + 52.614 with an R squared value of 0.91. This close correlation to a linear equation shows that the data fit the linear-decay trend well. Linear decay is common in near-field inductive coupling devices. Therefore, our device likely uses near-field inductive coupling. The electric potential output readings demonstrated that the passive stimulator device was capable of producing significant voltage pulses when physically-uncoupled from a source of near-field VHF. To further our research, we next investigated if those pulses were of sufficient power to elicit responses from electrically excitable tissues.

While applying VHF waves to the device at 15 cm, we observed two contractions in the amputated leg at the femur and tibia joint and the tibia and tarsus joint when the RF source was up to 90 cm away in all cricket legs (Fig. 2).

Figure 2: After stimulation, the cricket tibia swung to the right and then returned to its original position. Then, the cricket femur swung to the left before returning to its original position.

The two leg positions in Figure 2 are overlaid photos of the leg from the beginning and end of the movement. The highlighted area shows the range of motion between each contraction. All 20 cricket legs contracted first at the tarsus and then the tibia before returning to the starting position in under two seconds. However, the angle of contraction decreased as the RF source moved away from the cricket leg.

Discussion

The data show that near-field inductive coupling can power an external stimulation device. The linear decay between the RF source and significant voltage output demonstrate that near-field inductive coupling principally powers the device. We have also shown that the stimulation from our external prototype device promotes biological responses from recently harvested cricket tissue. The data support the hypothesis that our device is powered by near-field inductive coupling and capable of stimulation.

The proximate distance of 70 cm or less between device and RF source allows a person to stimulate excitable tissue within themselves by holding a controlling device within their hand or stimulating excitable tissue in a model organism at close distance (Permutter et al., 2006). The requisite proximity of device and RF source is beneficial because it decreases the likelihood of signal interference and cyber security threats to medical records.

This device sets the stage for future wireless neurostimulators, but needs further development before use in preclinical or clinical settings. The stimulation pulse pattern is determined entirely by the keying on and off of the RF source, which limits the regularity and precision of stimulation in sensitive tissues like the brain. Making a smaller circuit is necessary to facilitate human and model organism use. The relative inefficiency of reduced-length antennas limits decreasing the size of the circuit. Using higher frequencies, such as microwaves, to power the device would allow for a smaller antenna length while maintaining a stimulus effect. Future research should create a frequency discriminatory system to stimulate tissue at a precise voltage at regular time intervals and further miniaturize the device. Future research should also test the stimulation effect in fresh vertebrate cadaver tissue and eventually preclinical animal models.

Radio waves provide an affordable source of inductive coupling capable of powering a deep brain tissue stimulation device. The radio-wave-powered inductive coupling used to power this device cannot discriminate between multiple stimulation leads nor efficiently control the voltage output of multiple stimulation leads. Future research should develop a device to discretely control multiple devices at different sites within a body. To control one stimulation site independently from another, when multiple devices are attached to different target sites, the device needs a very high Q resonance circuit. The high Q resonance circuits would respond more selectively to one assigned frequency, as opposed to powering and controlling this type of device. Due to the increased selectivity, many miniature devices might be implanted in different regions of the brain and independently controlled by specific frequencies (Dongjin et al., 2013). This is important if a patient needed different stimulation voltages for different areas of their brain. Furthermore, a passive, inductively-powered device, such as the device from the present study, could be implanted permanently and serve as a brain-machine interface that remains viable throughout the lifetime of the research animal or patient, with no need for battery replacement, no generation of excess heat, or complications from wires. This device must go through many casing, packaging, miniaturizing, and stimulation specificity developments and design improvements before use in pre-clinical or clinical research and therapies.

Despite the need for future research, this device is a first step toward the development of an implantable device that is powered and controlled wirelessly by VHF or UHF energy. This device establishes a baseline prototype for miniature, smooth wireless devices that do not produce unsafe heat or create unnecessary pathways to infection. A more optimized device would help further treatment for Parkinson's Disease, depression, and other conditions that can be alleviated with neural or motor tissue stimulation powered by inductive coupling.

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