Implantation of WFMA Stimulators in Macaque

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***Abstract*— Our project to develop an intracortical visual prosthesis has motivated the design, fabrication, and testing of a Wireless Floating Microelectrode Array (WFMA) stimulator. This implantable device can be used for an electrical stimulation interface in the peripheral and the central nervous system. Previously, its use in a sciatic nerve rodent model was described. Here implantation of two WFMAs in motor cortex of two NHP (macaque – two devices/animal) is described. Preliminary functional testing show the implanted devices to be fully functional with stimulation-induced motor movements obtained. Functional testing is on-going.**

I. Introduction

Despite enhanced manufacturing methods, and widespread use of cortical electrode arrays for recording and stimulation, most intracortical systems have limited implanted lifetimes substantially due to issues related to the reliability of percutaneous connector systems [1,2]. There has been progress overcoming the limitations of connector-based systems through the use of implantable devices that are powered by, and communicated with, wireless means, especially for cochlear implants and other functional neural stimulators [3]. These approaches do not fully eliminate the tethering cable that connects to the electrode structures. For an intracortical system, elimination of the tethering cable is generally regarded as highly desirable in order to allow the electrode arrays to "float" with the brain. Full integration of wireless electronics within an implantable intracortical array has historically been very challenging, and reports in the literature have been limited to in-vitro demonstrations, acute non-survival animal studies, or hybrid demonstrations that utilize some form of primary power other than a wireless source [4][5]. The design of fully wireless systems that integrate electronics with electrode arrays have notable challenges related to packaging and biocompatibility (physical and material) with the cortex [6]. As part of our Intracortical Visual Prosthesis (ICVP) development, we have developed a wireless intracortical stimulating electrode device intended for long-term cortical implantation in humans. The WFMA is a wireless intracortical stimulation device that provides constant-current charge-balanced electrode driving, and the sending of reverse telemetry of electrode voltage waveforms for sixteen activated iridium oxide film (AIROF) electrodes. We have previously reported the use of the WFMA for chronic implantation in rat sciatic nerve. [7,8,9], and these implanted devices have remained functional for approximately 16 months, until animal euthanasia. Here, we report the implantation and preliminary functional testing of the WFMA in motor cortex of Macaque. These surgical experiences in non-human primate, have particular significance for a planned clinical trial of the ICVP in humans.

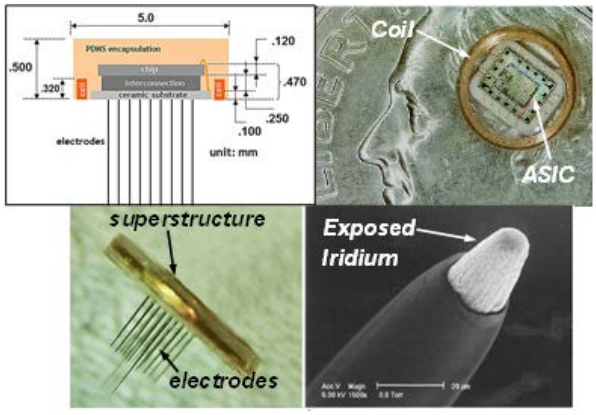

Figure 1. - Details of the WFMA stimulator module. Top Left: Sectional drawing of WFMA – for clarity not all drawing dimensions to scale. Top Right: Top view of WFMA on US Dime. Bot Left: Side view of WFMA showing electrodes. D. SEM photograph of typical AIROF electrode; black is Parylene insulation, bright is iridium

II. Material and Methods

A. WFMA Description

The physical structure of the WFMA is shown in Fig 1, and the function has been described in [7,8,9].Each WFMA contains 16 AIROF electrodes combined with wireless electronics that allows for powering and communication over a transcutaneous inductive link operating at 5MHz.

WFMA base structures that contained the electrodes within the ceramic superstructure base were fabricated by Microprobe for Life Science (MLS) and sent to the Illinois Institute of Technology (IIT). At IIT, the WFMA base structure was completed into a WFMA by the addition of the application-specific-integrated circuit (ASIC), the power/communication coil, and the polymeric encapsulation. Following WFMA encapsulation curing, the electrodes were activated via the wireless link as described in [10].

Testing of WFMA mechanical samples, using a high-speed insertion tool [11] was done to refine the tool electrical driving parameters so that the insertion speed reached 1-2 m/sec. Consistent with the design of the insertion tool, the WFMA devices were loaded into the tool collets and the WFMAs with the tool were subjected to Sterrad. This procedure was repeated for implantations in two Rhesus monkeys (macaque), with surgical procedures separated about 2 weeks apart.

B. Surgical Description

The surgical implantations followed an approved animal protocol at the University of Chicago, with some procedural differences between the two surgeries being related to other hardware implanted at the time of WFMA implantations.

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The other hardware supports auxiliary testing with the animals not related to the WFMA testing.

For both surgical procedures: After sedation and intubation, the animal was placed in prone position, and the head was fixed in a parallel bar stereotaxic frame. The hair on the head was clipped, and the cranial vault area above the ears was prepped with iodine-based solution. A longitudinal incision of the scalp was made along the midline, and the scalp spread with sutures. The likely location of the motor strip was accomplished by measurement of the distance from orbits and occiput based on imaging, and by skull landmarks such as the coronal suture. A craniotomy was performed measuring approximately 2.5cm by 2 cm. After hemostasis, a durotomy was performed with a scalpel and microscissors. The leaflets of the dura were retracted. Surface cortical stimulation was done with hand-held electrodes while observing the animal's hand and face, resulting in the identification of the motor strip, specifically relative to the face and hand motor areas. To insert the WFMAs into the cortex, the electromechanical insertion tool was attached to a 6 axis manipulator connected to the stereotactic frame. After adjusting the manipulator so that the tip of the insertion tool was appropriately located, and perpendicular to the brain, the collect containing the WFMA was loaded into the tool, and electric drive to the tool motor was triggered. This procedure was repeated for a second WFMA device. After implantation, we approximated the dural leaflets were approximated, and covered with a layer of gelfoam.

III. Results

Fig 2 shows the WFMA devices implanted into the brain for the first of the two animals. The WFMAs implantations

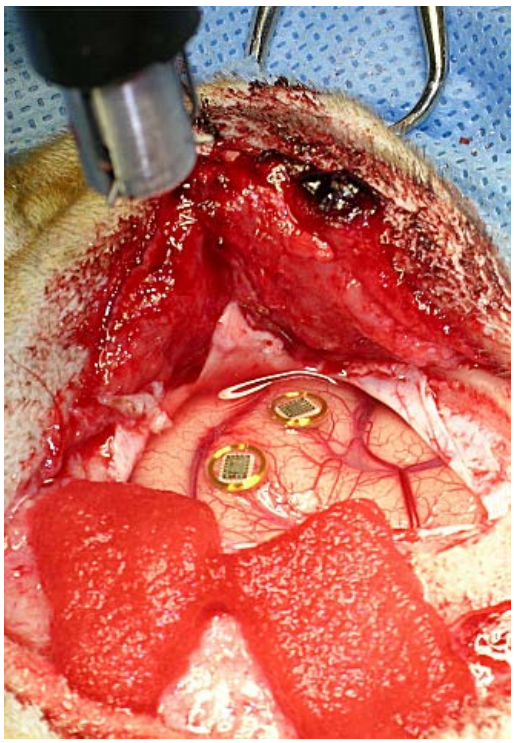

Figure 2. – Photograph of two WFMA stimulators implanted in motor cortex of macaque. Note the tip of the inserter tool above the implanted WFMAs, after withdrawal, immediately following insertion.

were successfully accomplished as evidenced by the visual observation of no surface blood vessel leakage and stable post-insertion positioning. Immediately following the surgery, after scalp closure, the electrical operation of the WFMAs was confirmed by verifying command and reverse telemetry communication with the implanted devices.

Functional testing of the WFMAs, in both animals is on-going, with preliminary results available at the time of this writing. Initial testing of the first animal, one week post implant, showed continued electrical operation and visual evidence of hand and face movements caused by the wireless commanding of the WFMAs. Due to anesthesia time limits in this first testing session, more extensive testing in the awake animal is scheduled for the near future. Initial testing while under anesthesia in the second animal showed electrical operation of the WFMAs as evidenced by the reverse telemetry. Voltage transients, via reverse telemetry, for 30uA of stimulation current were recorded for all 32 electrodes. Space limitations do not permit comprehensive reporting of all waveshapes. Representative waveshapes for one electrode is shown in Fig 3. Testing of both animals is on-going, albeit with some challenges coordinating the primate training with the visual observations of the stimulation induced motor activity and the configuration of extracorporeal telemetry controller units.

IV. Discussion

The reverse telemetry with the transmission of diagnostic information about the operation of the WFMAs and the electrode voltage transient waveforms is extremely helpful for knowing that the implanted devices are electrically functional and that they are delivering current through the electrodes. As long as the electrode polarization is not excessive (i.e. exceeding the water window), the programmed stimulation current is being delivered in an electrochemically "safe" manner. It is interesting to note that for the in-vivo transient shown in Fig 3, most of the voltage drop is associated with access resistance rather than polarization. This suggests that thinner AIROF films might be used to reduce the overall magnitude of the transient. Paradoxically, an electrode that has lower charge capacity in-vitro may have an overall lower total voltage excursion when used in-vivo if the magnitude of the voltage transient were to be less. This issue requires further study which we are pursuing in a cortical rodent model.

V. Conclusion

Implantation of WFMAs in cortex using high-speed insertion seems feasible and may form the basis for studies with larger numbers of devices. We expect that the chronic functionality of these cortical WFMAs may follow that of the peripheral rodent WFMA studies, and months of experimental results may be obtained. These first-ever demonstrations of WFMA cortical implantation are significant in that a fully implantable 16-channel intracortical stimulator requiring no percutaneous connection has numerous uses for neural modulation within motor and sensory cortex.

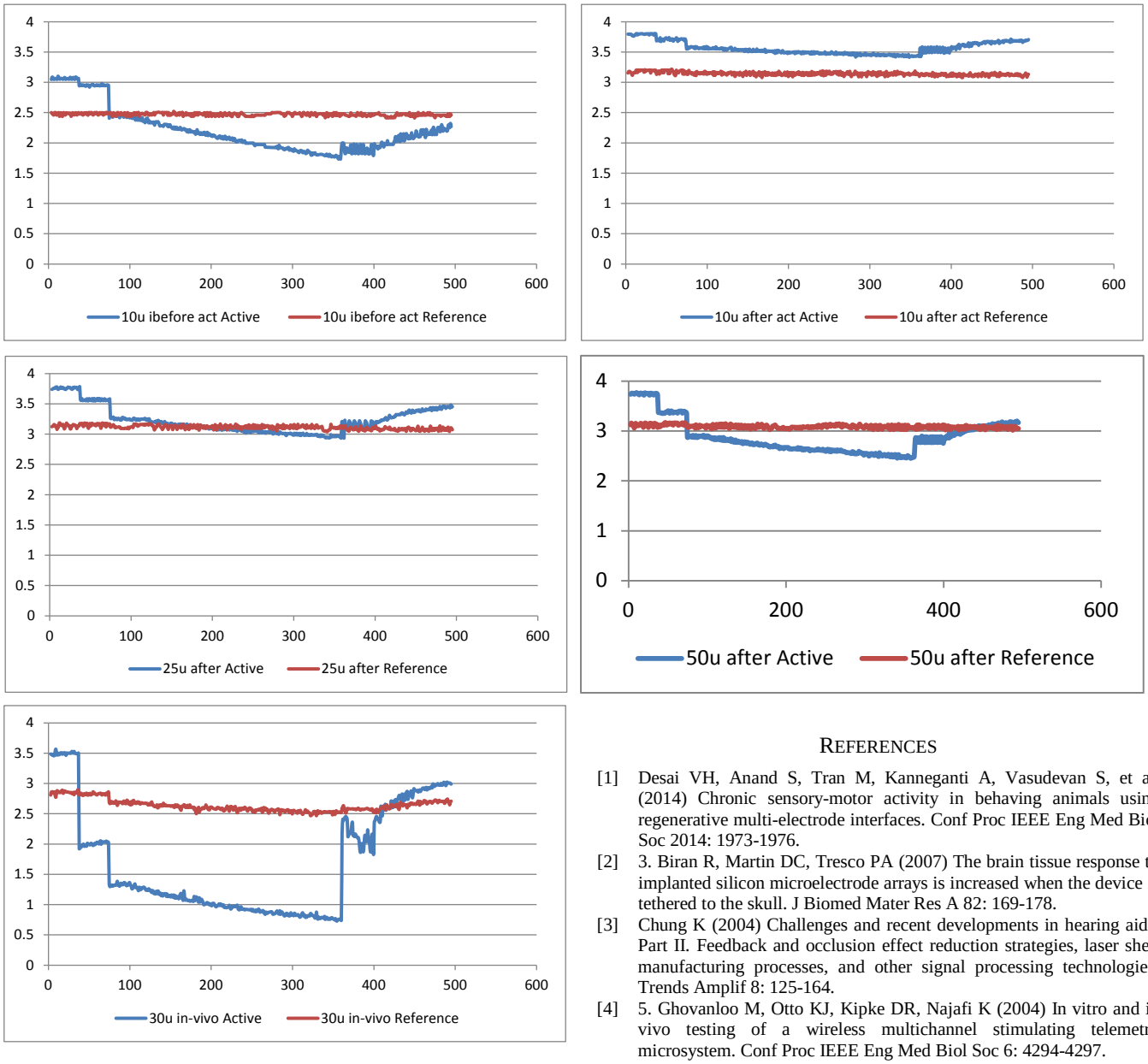

Figure 3. – Electrode voltage transient plots taken via reverse telemetry from WFMA. Top Right: 10u before iridium activation; Top Left: 10uA after activation; Mid Right: 25uA after activation; Mid Left; 50uA after activation; Bot Right: 30uA in-vivo.

REFERENCES

[1] Desai VH, Anand S, Tran M, Kanneganti A, Vasudevan S, et al. (2014) Chronic sensory-motor activity in behaving animals using regenerative multi-electrode interfaces. Conf Proc IEEE Eng Med Biol Soc 2014: 1973-1976.

[2] 3. Biran R, Martin DC, Tresco PA (2007) The brain tissue response to implanted silicon microelectrode arrays is increased when the device is tethered to the skull. J Biomed Mater Res A 82: 169-178.

[3] Chung K (2004) Challenges and recent developments in hearing aids. Part II. Feedback and occlusion effect reduction strategies, laser shell manufacturing processes, and other signal processing technologies. Trends Amplif 8: 125-164.

[4] 5. Ghovanloo M, Otto KJ, Kipke DR, Najafi K (2004) In vitro and in vivo testing of a wireless multichannel stimulating telemetry microsystem. Conf Proc IEEE Eng Med Biol Soc 6: 4294-4297.

[5] 6. Sharma A, Rieth L, Tathireddy P, Harrison R, Oppermann H, et al. (2011) Long term in vitro functional stability and recording longevity of fully integrated wireless neural interfaces based on the Utah Slant Electrode Array. J Neural Eng 8: 045004.

[6] 7. Xie X, Rieth L, Williams L, Negi S, Bhandari R, et al. (2014) Long-term reliability of Al2O3 and Parylene C bilayer encapsulated Utah electrode array based neural interfaces for chronic implantation. J Neural Eng 11: 026016.

[7] P. Troyk et al., "In-vivo tests of a 16-channel implantable wireless neural stimulator," Neural Engineering (NER), 2015 7th International IEEE/EMBS Conference on, Montpellier, 2015, pp. 474-477.

[8] S. Bredeson, A. Kanneganti, F. Deku, S. Cogan, M. Romero-Ortega and P. Troyk, "Chronic in-vivo testing of a 16-channel implantable wireless neural stimulator," Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE, Milan, 2015, pp. 1017-1020.

[9] M. Romero-Ortega Aswini Kanneganti ; Geetanjali Bendale ; Jennifer Seifert ; Samuel Bredeson ; Philip Troyk ; Felix Deku ; Stuart Cogan, "Chronic and low charge injection wireless intraneural stimulation in vivo," Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE, Milan, 2015, pp. 1013-1016.

[10] Hu, Z; PR Troyk, GA DeMichele, K Kayvani, S Suh, "Intrinsic activation of iridium electrodes over a wireless link," 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 2788-2791, Aug 2012.

[11] Bredeson, SD; PR Troyk. "Device for the implantation of neural electrode arrays," 36th Annual International Conference of the IEEE EMBS, pp. 434-437, Aug 2014.