33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

# Real-time communication of head velocity and acceleration for an externally mounted vestibular prosthesis

James O. Phillips, Steven M. Bierer, Leo Ling, Kaibao Nie, and Jay T. Rubinstein, *Member, IEEE*

*Abstract*—**Loss of vestibular function results in imbalance, disorientation, and oscillopsia. Several groups have designed and constructed implantable devices to restore vestibular function through electrical stimulation of the vestibular nerve. We have designed a two-part device in which the head motion sensing and signal processing elements are externally mounted to the head, and are coupled through an inductive link to a receiver stimulator that is based on a cochlear implant. The implanted electrode arrays are designed to preserve rotational sensitivity in the implanted ear. We have tested the device in rhesus monkeys by rotating the animals in the plane of the implanted canals, and then using head velocity and acceleration signals to drive electrical stimulation of the vestibular system. Combined electrical and rotational stimulation results in a summation of responses, so that one can control the modulation of eye velocity induced by sinusoidal yaw rotation.**

## I. Introduction

THERE are currently few effective clinical strategies for the restoration of vestibular function following loss of hair cells in the vestibular labyrinth. Wall and colleagues have demonstrated that non-invasive balance prostheses may provide partial compensation by stimulating other sensory systems with balance information [1]. Several investigators have demonstrated that a device similar to a cochlear implant could be used to electrically stimulate vestibular afferents, while using accelerometers, gyroscopes, and/or rate sensors to transduce head motion and drive the stimulation in real-time [2]-[18]. The electrical stimulus would restore the afferent signal carried by the vestibular nerve, producing a restoration of movement-elicited behavior. A partial loss of vestibular function could also be treated with this strategy if the prosthesis allowed natural sensation of rotation by the remaining intact hair cells. Such a treatment would also require that electrical stimulation could be combined with natural stimulation to produce a summed response. Unfortunately, the current designs of vestibular prostheses have many limitations and there is much that we do not know. Most devices are implanted in the ampullae of individual canals, which potentially compromises natural vestibular sensitivity of the implanted ear. The devices are also constructed to be totally implantable, which poses challenges in terms of power consumption and reliability, and limits the upgradability of the device. Finally, the processing of the transduced rotation signals and the required hardware are limited by our existing knowledge of the stimulation parameters that will optimally drive vestibular responses. To address these issues, we have constructed a two-part vestibular prosthesis that is based on a highly reliable cochlear implant design. The receiver stimulator is a modified Nucleus Freedom cochlear implant from Cochlear Limited. The electrode arrays are designed to preserve rotational function in the implanted ear. The high power components and signal processors are externally placed, and utilize the inductive link of the device to communicate rotational signals in real-time. In this paper we describe the design of the real-time interface between the rotation sensor and the receiver stimulator. We also show experiments which demonstrate the real-time performance of the device and the interaction between been electrical stimulation and preserved natural rotational sensitivity.

Manuscript received April 15, 2011. This work was supported in part by the National Institute on Deafness and Other Communication Disorders under contract N01-DC-6-005, and a grant from the Wallace H. Coulter Translational Research Partnership Program. Technical support was provided by Cochlear Limited, Lane Cove, Australia. The University of Washington and all authors have intellectual property associated with this project.

J. O. Phillips is with the Department of Otolaryngology and the Virginia Merrill Bloedel Hearing Research Center at the University of Washington, Seattle, WA, 98195, USA (phone: 206-543-0265; fax: 206-616-1828; e-mail: jop@u.washington.edu).

S. M. Bierer is with the Department of Otolaryngology at the University of Washington, Seattle, WA, 98195, USA.

L. Ling is with the Department of Otolaryngology at the University of Washington, Seattle, WA, 98195, USA.

K. Nie is with the Department of Otolaryngology and the Virginia Merrill Bloedel Hearing Research Center at the University of Washington, Seattle, WA, 98195, USA.

J. T. Rubinstein is with the Department of Otolaryngology, the Department of Bioengineering, and the Virginia Merrill Bloedel Hearing Research Center at the University of Washington, Seattle, WA, 98195, USA.

## II. Procedure

### A. Vestibular Implant Design

The vestibular implant is based on the Nucleus Freedom cochlear implant and consists of a receiver stimulator, three stimulation leads and a remote ball ground. The leads have a thin (approximately 140 μm diameter) distal tip that is about 2.5 mm in length, which is designed to be inserted in the perilymphatic space adjacent to the ampulla of each semicircular canal. Each lead contains three independent stimulation sites that are 200-250 μm in length. The inserted tips are designed not to occlude the lumen of the membranous labyrinth, and they are implanted without impinging on the crista ampularis, thereby preserving the rotational sensitivity of the implanted canal. Figure 1 displays the receiver stimulator and the modified leads. The inset shows a magnified view of the stimulation sites at the

978-1-4244-4122-8/11/$26.00 ©2011 IEEE

tip of each lead.

The receiver stimulator can be driven by either a NIC 2 (Nuclear Interface Communicator) research platform for preprogrammed stimulation of the vestibular nerve, or directly via a standard clinical processor. The NIC 2 can produce patterned electrical stimuli that do not require a head-related input signal. The central component of the implant control software is a graphical user interface (GUI) written in the MATLAB programming environment. By filling in text fields or selecting from pull-down menus, the user has control over numerous stimulus parameters, such as pulse width (phase) and amplitude. Active and return electrodes can be configured for the monopolar or bipolar modes of stimulation. By manipulating the duration parameter, a single pulse or train of pulses can be chosen. In addition, a pulse train can be sinusoidally amplitude-modulated or frequency-modulated based on specified modulation limits and oscillation rate. Finally, most of the stimulus parameters can be "vectorized" by specifying the first and last elements and a step size (which can be linear or logarithmic). During an experiment, all permutations of the vectorized stimulus parameters are delivered (optionally in a randomized order), separated in time by a user-selected inter-stimulus interval. The specified parameters are stored for future data analysis.

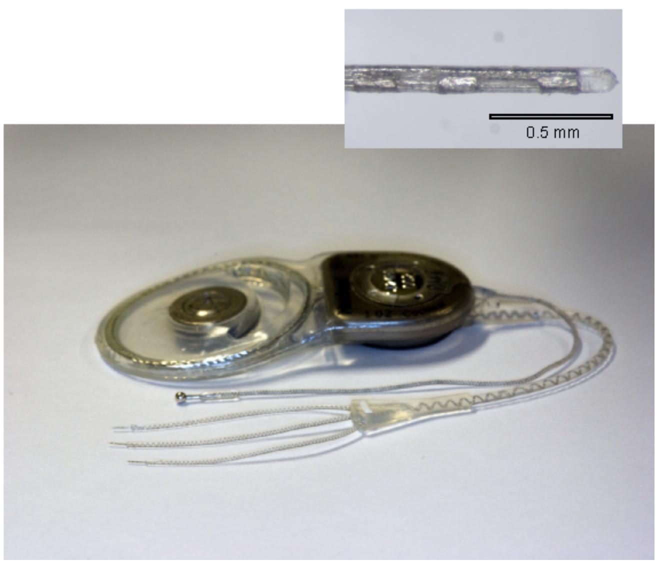


Fig. 1. Receiver stimulator and modified leads for a vestibular prosthesis. Inset above shows a magnified view of the individual stimulation sites.

The GUI software controls an L34 speech processor via the NIC 2 research interface. Since the MATLAB toolbox for NIC 2 does not support the bipolar stimulation mode and is limited in the number of pulse repeats that it can make, we have incorporated the Python programming language to interface with the L34 processor. The additional data exchange between MATLAB and Python was implemented using the Python 'io' module which has the capability of loading and saving MATLAB variables. As currently implemented, the MATLAB GUI calls the customized Python code to generate a pulse sequence and stream it to the speech processor.

For real-time operation in the laboratory, we extract head position signals from a magnetic coil system (C-N-C engineering). The position signals are then differentiated to provide position and velocity voltage signals, which are interfaced with a Cochlear Freedom clinical processor. The interface offers fast triggering of brief pulse trains over a range of voltage-controlled current levels and is implemented in the MATLAB programming environment, allowing continuous modulation of pulse trains based on an external signal (e.g. chair velocity) and non-linear voltage-to-current transformation.

The stimulus interface was programmed in the MATLAB Simulink environment, using the Signal Processing Blockset, Real-Time Workshop, and Real-Time Windows Target toolboxes. The two modes of the program are shown as block diagrams in Figure 2, for single-channel processing. Both modes acquire and deliver signals with a data acquisition board (National Instruments PCI-MIO-16XE-50). In trigger mode (Figure 1A), a TTL pulse initiates a waveform (band limited to ~100 Hz) that modulates a 1 kHz sinusoidal carrier. The resulting AM signal is conveyed to the output channel of the DAQ board, conditioned with an audio amplifier, and sent to the auxiliary audio jack of the clinical interface. In signal mode (Fig. 2B), the modulating input signal is itself acquired and appropriately transformed before mixing with the carrier.

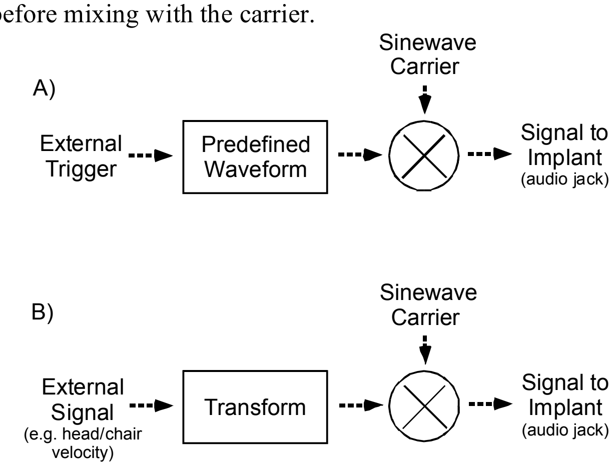


Fig. 2. Block diagrams of the stimulus delivery Simulink program for (A) trigger mode and (B) stimulus mode.

While only one modulation/stimulation channel is illustrated in Fig. 2b, multiple channels are handled by mixing each modulation signal with a different carrier frequency. The MATLAB-based interface program directs a National Instruments data acquisition board to read in three band-limited signals (e.g. velocity signals from a rotational sensor), transforms and mixes each with a different sinusoidal carrier waveform, and outputs the summed signal to the speech processor. The processor, which is set up using the standard clinical software, spectrally separates the composite signal back into three channels and delivers pulses to the designated electrodes at current levels modulated by each channel's time-varying signal amplitude.

### B. Testing, Implantation, and Recording

To test the device on the bench we used an "implant-in-a –box", which externalizes the outputs of the receiver stimulator. For in-vivo behavioral testing, we implanted the receiver stimulator in rhesus monkeys during a sterile surgery in which we placed electrodes in the lateral and posterior semicircular canals. All experiments were performed in accordance with the recommendations of the National Research Council (1997, 2003) and the Society for Neuroscience, and exceeded the minimal requirements recommended by the Institute of Laboratory Animal Resource and the Association for Assessment and Accreditation of Laboratory Animal Care International. All procedures were evaluated and approved by the Institutional Animal Care and Use Committee of the University of Washington.

We recorded eye movement with an electromagnetic technique, which involved the surgical implantation of a search coil on one eye in a sterile surgery [19]. In the same surgery, preformed acrylic stabilization lugs were placed on the skull of the monkey to allow stabilization of the animal's head. A coil affixed to the stabilization lug was used to record head position. A second sterile surgery was performed to implant the receiver stimulator of the vestibular prosthesis one month after recovery from the first surgery.

The recovered animal was placed in a primate chair, which in turn was placed within a magnetic field (CNC, Seattle). The primate chair was attached to a 3-dimensional rotator that was capable of rotating the animal in the planes of the implanted canals. The animal sat facing a tangent screen that rotated with the animal. We rewarded the animal with applesauce for redirecting its gaze with an accuracy of ±2° between sequentially illuminated spots projected with a 2-dimensional laser mirror galvanometer. During electrical stimulation trials, the laser spot was extinguished before the presentation of the electrical stimulus.

Analog voltages proportional to eye, head, chair, and target position, the driving signal input to the stimulator, and the electrical stimulation artifact were digitized on-line with a CED interface and a PC computer. Behavioral signals were digitized at 1 kHz. The digitized data were analyzed with the aid of an interactive program that displayed the stimulus and behavioral channels, and separated slow and fast phase eye movements based on an adjustable velocity criterion. We calculated average slow phase velocity for nystagmus, or the gain, phase and offset of sinusoidally modulated eye velocity resulting from activation of the vestibulo-ocular reflex (VOR) with sinusoidal chair rotation or sinusoidal current amplitude modulated electrical stimulation. In addition, we calculated the gain and offset of sinusoidal eye movement resulting from combinations of sinusoidal rotation and constant frequency and constant current amplitude electrical stimulation.

## III. Results

We implanted 8 rhesus monkeys with the vestibular prosthesis. All monkeys were implanted with electrodes in the lateral and posterior semicircular canal. One monkey was also implanted with electrodes in the superior canal. All but one monkey had electrodes that elicited constant velocity slow phase eye movements largely in the plane of the implanted canal in response to constant frequency and constant current amplitude electrical stimulation with short biphasic pulses. Figure 3 shows the result of one such stimulation experiment. 150 pps monopolar electrical stimulation of the right lateral canal, with a return to the remote ground, at 87μA, 400 μs/phase, 8μs interphase gap for 10 s duration produced a largely right-beating constant velocity nystagmus. A weak down-beating component was also seen, probably due to current spread to the adjacent vertical canal. Increasing stimulation current increased the slow phase velocity of the nystagmus (see below).

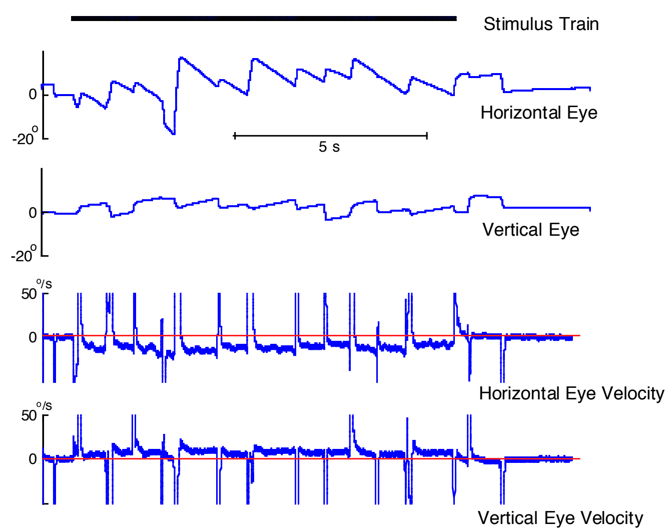


Fig. 3. Eye movements resulting from constant frequency and amplitude stimulation of the right lateral canal. Horizontal and vertical eye position and velocity are displayed. The horizontal bar (stimulus train) indicates the duration of stimulation.

### A. Bench Testing

To evaluate the performance of real-time vestibular stimulation, we performed bench testing of the vestibular prosthesis. Testing of the signal delivery program was performed using an "implant-in-a-box", with each output channel connected to ground via a 10 kOhm resistor. An example of pulse trains modulated simultaneously with three distinct input signals is shown in Figure 4. The input signals (left panel) were generated with separate function generators and the resulting pulse trains (right panel) were delivered to implant channels 3 (top), 6 (middle), and 9 (bottom), corresponding to the most distal electrode pad of an implanted prosthesis. Each channel was programmed to produce biphasic pulses with a width of 100 µs per phase, at a rate of 500 pps, and with minimum and maximum currents at 0 and 650 µA, respectively. The carrier frequencies were 800, 2000, and 5000 Hz, and the analysis bandwidths were at least one-half octaves. Channels 3 and 6 were programmed with a linear transformation for an input range of +/- 10 volts. As a demonstration of the programming flexibility, channel 9 was programmed with a ½-wave rectified transformation for an input range of +/- 5 volts. Comparison of the left and right panels shows that the different input signals resulted in the expected modulation of the three pulse trains. Figure 4 shows that the signal interface program performs well in separating the three components without cross talk between channels.

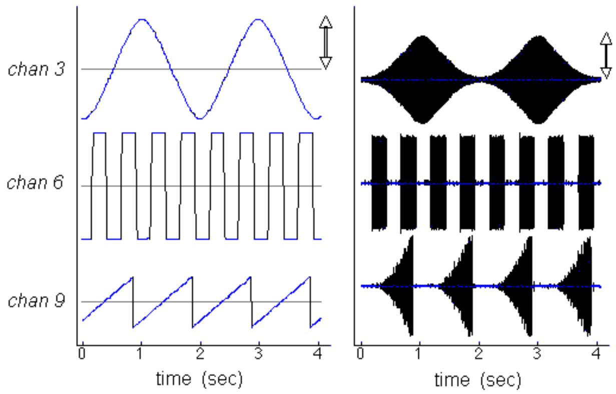


Fig. 4. 3-channel independent electrical stimulation assessed with an "implant in a box". The input signals are displayed in the left panels and the output stimulation measured across a resistor is displayed in the right panels. The vertical arrows indicate 10 V and 650 µA, respectively.

## B. *In-vivo testing*

To evaluate the effect of electrical stimulation in vivo we performed stimulation experiments with trains of constant frequency and constant current amplitude stimuli, either alone, as shown in Figure 3, or in combination with rotation in the plane of the stimulated canal, as shown in Figure 5. Sinusoidal rotation produced sinusoidal modulation of slow phase eye velocity. Electrical stimulation in combination with sinusoidal rotation produced an offset in slow phase eye velocity, corresponding to a constant velocity nystagmus that was elicited by electrical stimulation alone. In Figure 5, the modulated horizontal eye velocity in the left panel results from sinusoidal yaw rotation. The modulated eye velocity in the right panel, which is biased toward leftward slow phase eye velocity, results from the combination of yaw rotation and constant frequency and constant amplitude electrical stimulation of the right lateral semicircular canal. In this panel, the modulation appears unchanged, but there is a shift in the overall velocity.

When we changed the stimulation current, the offset velocity was changed, but the depth of modulation of velocity remained constant. This is shown in Figure 6, which displays the size of the velocity bias (dc shift) versus the stimulation current for electrical stimulation alone, and the depth of modulation (response amplitude) for a number of different stimulation current amplitudes. The left panel of Figure 6 shows that the leftward slow phase eye velocity increases with increasing stimulation current for control stimulations without rotation, and for stimulations combined with sinusoidal rotations at 0.25, 0.5 and 1.0 Hz. The size of the offset, or slow phase velocity bias, is quite similar in each condition for a given current amplitude. Furthermore, the right panel of Figure 6 demonstrates that the depth of slow phase eye velocity modulation in response to rotation combined with electrical stimulation remains relatively constant across stimulation currents from 70 to 130 µA, increasing only at the highest stimulation currents for the lower rotational frequencies. Taken together, the data of Figures 5 and 6 suggest that there is a summation of natural vestibular responses and concurrent electrical stimulation with a vestibular prosthesis.

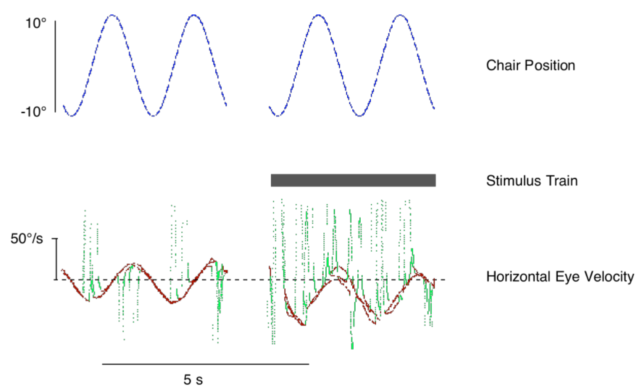


Fig 5. Horizontal eye velocity resulting from sinusoidal yaw rotation with and without electrical stimulation of the right lateral canal. Chair position, horizontal eye velocity and stimulus train are displayed. The dashed horizontal line represents zero velocity.

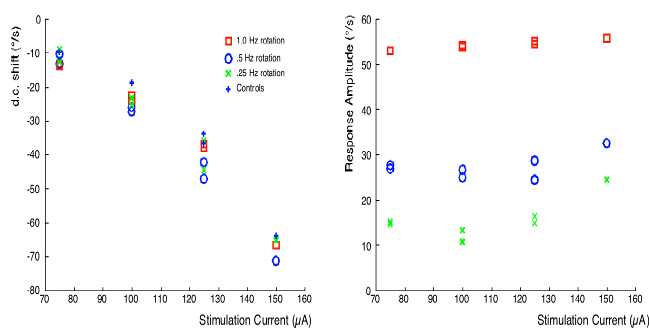


Fig 6. Horizontal eye velocity bias (dc shift) and depth of modulation (response amplitude) resulting from electrical stimulation at different current levels during sinusoidal yaw rotation at several frequencies, or during electrical stimulation without yaw rotation (control).

In order to extend our observations to real-time modulated electrical stimulation in-vivo, we performed a final stimulation experiment. We combined rotation with real-time head velocity contingent amplitude modulated vestibular stimulation. The results of this experiment are seen in Figure 7A, which shows that sinusoidally modulated eye velocity resulting from sinusoidal yaw rotation can be effectively eliminated by amplitude modulated electrical stimulation from a vestibular implant. Essentially, summation of the natural vestibular response to rotation, and the response to real-time modulated electrical stimulation, results in cancellation of modulated eye velocity. Furthermore, increasing the amplitude of the sinusoidal yaw stimulus in Figure 7B effectively increases the peak velocity of the stimulus but also increases the depth of the modulation in stimulation current so the prosthesis compensates in real-time for the change and maintains the cancellation.

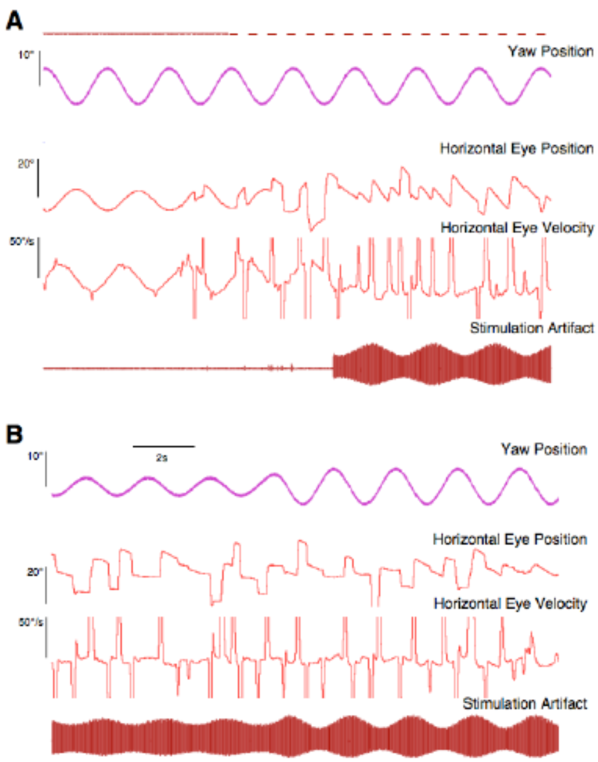


Fig 7. Horizontal eye velocity and position resulting from combinations of sinusoidal yaw rotation and real-time amplitude modulated electrical stimulation of the lateral canal afferents. A. Traces from top to bottom are visual target on (solid) and off (dashed line), yaw head position, horizontal eye position, horizontal eye velocity and stimulation artifact. B. Traces from top to bottom are yaw head position, horizontal eye position, horizontal eye velocity and stimulation artifact

## IV. Conclusion

We have presented data suggesting that a two-part vestibular prosthesis can produce real-time stimulation that is appropriate to modify ongoing natural vestibular responses in a predictable manner. This technology may be useful in the treatment of total or partial vestibular loss.

## References


[1] Wall C 3rd, Kentala E. Effect of displacement, velocity, and combined vibrotactile tilt feedback on postural control of vestibulopathic subjects. J Vestib Res. 2010; 20(1):61-9.

[2] Hayden R, Sawyer S, Frey E, Mori S, Migliaccio AA, Della Santina CC.Virtual labyrinth model of vestibular afferent excitation via implanted electrodes: validation and application to design of a multichannel vestibular prosthesis. Exp Brain Res. 2011 May;210(3-4):623-40. Epub 2011 Mar 6.

[3] Dai C, Fridman GY, Chiang B, Davidovics NS, Melvin TA, Cullen KE, Della Santina CC. Cross-axis adaptation improves 3D vestibulo-ocular reflex alignment during chronic stimulation via a head-mounted multichannel vestibular prosthesis. Exp Brain Res. 2011 May; 210 (3-4): 595-606. Epub 2011 Mar 4.

[4] Dai C, Fridman GY, Della Santina CC. Effects of vestibular prosthesis electrode implantation and stimulation on hearing in rhesus monkeys. Hear Res. 2010 Dec 31.

[5] Davidovics NS, Fridman GY, Chiang B, Della Santina CC. Effects of biphasic current pulse frequency, amplitude, duration, and interphase gap on eye movement responses to prosthetic electrical stimulation of the vestibular nerve. IEEE Trans Neural Syst Rehabil Eng. 2011 Feb; 19(1): 84-94. Epub 2010 Sep 2.

[6] Fridman GY, Davidovics NS, Dai C, Migliaccio AA, Della Santina CC. Vestibulo-ocular reflex responses to a multichannel vestibular prosthesis incorporating a 3D coordinate transformation for correction of misalignment. J Assoc Res Otolaryngol. 2010 Sep;11(3):367-81.

[7] Tang S, Melvin TA, Della Santina CC. Effects of semicircular canal electrode implantation on hearing in chinchillas. Acta Otolaryngol. 2009 May;129(5):481-6.

[8] Della Santina CC, Migliaccio AA, Patel AH. A multichannel semicircular canal neural prosthesis using electrical stimulation to restore 3-d vestibular sensation. IEEE Trans Biomed Eng. 2007 Jun;54(6 Pt 1):1016-30.

[9] Della Santina C, Migliaccio A, Patel A. Electrical stimulation to restore vestibular function development of a 3-d vestibular prosthesis. Conf Proc IEEE Eng Med Biol Soc. 2005;7:7380-5.

[10] Saginaw M, Gong W, Haburcakova C, Merfeld D. Attenuation of Eye Movements Evoked by a Vestibular Implant at the Frequency of the Baseline Pulse Rate. IEEE Trans Biomed Eng. 2010 Dec 3. [Epub ahead of print]

[11] Lewis RF, Haburcakova C, Gong W, Makary C, Merfeld DM. Vestibuloocular reflex adaptation investigated with chronic motion-modulated electrical stimulation of semicircular canal afferents. J Neurophysiol. 2010 Feb;103(2):1066-79. Epub 2009 Dec 16.

[12] Gong W, Haburcakova C, Merfeld DM.Vestibulo-ocular responses evoked via bilateral electrical stimulation of the lateral semicircular canals. IEEE Trans Biomed Eng. 2008 Nov;55(11):2608-19.

[13] Merfeld DM, Haburcakova C, Gong W, Lewis RF. Chronic vestibulo-ocular reflexes evoked by a vestibular prosthesis. IEEE Trans Biomed Eng. 2007 Jun;54(6 Pt 1):1005-15.

[14] Merfeld DM, Gong W, Morrissey J, Saginaw M, Haburcakova C, Lewis RF. Acclimation to chronic constant-rate peripheral stimulation provided by a vestibular prosthesis. IEEE Trans Biomed Eng. 2006 Nov;53(11):2362-72.

[15] Wall C 3rd, Merfeld DM, Rauch SD, Black FO. Vestibular prostheses: the engineering and biomedical issues. J Vestib Res. 2002-2003;12(2-3):95-113.

[16] Gong W, Merfeld DM. System design and performance of a unilateral horizontal semicircular canal prosthesis. IEEE Trans Biomed Eng. 2002 Feb;49(2):175-81.

[17] Gong W, Merfeld DM. Prototype neural semicircular canal prosthesis using patterned electrical stimulation. Ann Biomed Eng. 2000 May; 28(5): 572-81.

[18] Guyot JP, Sigrist A, Pelizzone M, Feigl GC, Kos MI. Eye movements in response to electrical stimulation of the lateral and superior ampullary nerves. Ann Otol Rhinol Laryngol. 2011 Feb;120(2):81-7.

[19] Judge SJ, Richmond BJ, Chu FC. Implantation of magnetic search coils for measurement of eye position: an improved method. Vision Res 1980; 20: 535–538.