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Introduction

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In 2001 the Association for Research in Otolaryngology (ARO) sponsored a symposium entitled, "Electrical Stimulation of the Vestibular System", at its midwinter meeting. The rationale and objectives of the symposium arose from observing the clinical success of cochlear implant technology for treatment of profound deafness. We were excited by the possibility that an implantable vestibular prosthesis could be developed for treatment and rehabilitation of vestibulopathic patients. At about the same time, we approached the Editors of JVR about their interest in publishing a vestibular prosthesis "white paper" that would review the state of the art, and identify the major issues that needed to be addressed in order to develop a prosthesis. Their response was to consider publishing the symposium talks together with the white paper. The result is this special issue on vestibular prostheses.

According to the NIH-NIDCD website, over 90 million Americans will seek medical attention for dizziness at least once in their lifetimes. A working committee report on vestibular disorders at the NIH found that at least 2 million Americans suffer or experience chronic impairment due to dizziness or imbalance, causing an annual medical cost exceeding $1 billion. Balance-related falls account for more than half of accidental deaths in the elderly. Many dizzy patients benefit from current treatments, but there remain a significant number who could potentially benefit from a safe and effective implantable prosthesis. Four patient "target groups" are identified and discussed in the White Paper authored by Wall, Merfeld, Rauch and Black.

The objective of the ARO symposium was to review the state-of-the-art of electrical stimulation in the vestibular system. The peripheral vestibular system is comprised of five anatomically separate endorgans sending tonic and phasic signals generated by linear and angular accelerations of the head to the central nervous system. This sensory input is used both for static and dynamic postural control, perception of self motion, and for maintenance of the vestibulo-ocular reflexes (VOR) that permit gaze stabilization during movement. The symposium began at the periphery with a review of hair cell responses to endolymphatic polarization and afferent responses to galvanic stimulation, followed systematically by talks on modeling electrical stimulation of the vestibular nerve, postural effects of galvanic stimulation, VOR effects of selective electrical stimulation in animals, and VOR and subjective responses to selective stimulation in humans. Although many aspects of cochlear implant technology may be directly transferable to vestibular implantation, there remain many unique anatomic, signal processing, and physiologic issues that are specific to a neural vestibular prosthesis.

It was the organizers' hope that this symposium would help define the directions where future research will yield the greatest benefit. The symposium comprised five talks: "Semicircular canal afferent and hair cell responses to electrical stimulation in perilymph and endolymph," by Richard Rabbitt of University of Utah; "Biophysical simulations for a vestibular prosthesis," by Jay Rubinstein of University of Iowa; "Enhancing human balance control with galvanic vestibular stimulation," by James Collins of Boston University; "Vestibulo-ocular responses induced by electrical stimulation in animals," by Dan Merfeld of Harvard Medical School; and "Selective electrical stimulation of human vestibular endorgans," by Steven Rauch of Harvard Medical School. The talks of Rubinstein, Collins, and Merfeld were subsequently submitted as papers to JVR, which the reader will find in this volume.

Rabbitt described the reliance of mechano-transduction and signal transmission by vestibular hair cells and afferent nerves upon ionic electrochemical gradients between intracellular and extracellular fluids. He summarized how these gradients could be perturbed by

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application of electrical or chemical stimuli, highlighting the ways in which modulation of electrochemical gradients acts upon different sets of hair cell and/or afferent neuron ion channels to effect differing neural responses. Afferent response dynamics elicited by these electrical stimuli were compared to each other and to those present during physiological head movements to illustrate both the effectiveness and also some of the limitations of electrical stimulation.

Rubinstein (see Rubenstein and DellaSantina) presented a model that theoretically allows one to control the regularity of the spike rate in vestibular afferents. The application for prosetheses is that it may be possible to mimic both irregular phasic or regular tonic units with a fairly simple stimulator.

Merfeld (see Lewis et al.) described a novel kind of cross-axis adaptation of the angular VOR. The implication for a prosthesis is that the central nervous system can adapt to produce responses in the "appropriate" direction, where "appropriate" is defined by the behavioral goal.

Collins (see Scinicariello et al.) presented results showing that monopolar galvanic vestibular stimulation (GVS) with a stochastic stimulus produces correlated anterioposterior postural sway. Mediolateral sway responses that are correlated with bipolar stochastic GVS have already been demonstrated. Collins demonstrated that a combination of monopolar and bipolar GVS should be able to produce sway in arbitrary directions.

Rauch presented preliminary experiences with attempts to selectively electrically stimulate the horizontal semicircular canal in human subjects. Rauch and collaborators hypothesized that a surface electrode applied at the site of a tympanomastoidectomy, a surgical treatment for chronic otitis media and cholesteatoma, could be used to deliver a biphasic pulse train that could elicit selective horizontal canal stimulation. This surgical procedure alters the anatomy of the temporal bone such that the bony otic capsule of the horizontal semicircular canal is visible just under the skin at the end of the ear canal. Two subjects who had undergone previous tympanomastoidectomy volunteered to have such stimulation. Eye movements were monitored by video oculography and subjective perceptual responses were elicited from the subjects throughout the test sessions. In both subjects, ramps of increasing stimulus intensity provoked perceived facial nerve activation and ipsilateral facial twitching before a definite vestibular percept or eye movement was detected. This suggests that a more invasive method, perhaps by intra-operative placement of temporary electrodes during labyrinthectomy surgery, will be needed to achieve selective stimulation of vestibular endorgans in humans.

The ARO symposium, "Electrical Stimulation of the Vestibular System," generated considerable interest in the clinical and research communities. A Vestibular Electric Stimulation (VES) Study Group has been formed. Current membership includes approximately 15 clinicians and scientists from around the United States, with membership open to all interested parties. Several investigators are actively pursuing vestibular electric stimulation research with NIH and other funding. In the future we hope to see growing interest in this field. It is now time for the NIH to consider sponsoring a conference on the topic of electric stimulation of the vestibular system, perhaps under the aegis of the Neural Prosthesis Program. There is no question about the clinical need for an implantable vestibular prosthesis. A forum for interactions among interested clinicians and scientists in otology/neurotology, neurology, and physical medicine, physiology, neuroscience, biomedical engineering, and materials science will help propel the field forward.

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