Hearing Research 350 (2017) 235–243

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

Modulation of auditory percepts by transcutaneous electrical stimulation

Margarete Anna Ueberfuhr [a, b], Amalia Braun [c], Lutz Wiegrebe [b, c], Benedikt Grothe [b, c], Markus Drexl [a, *]

[a] German Center for Vertigo and Balance Disorders, University Hospital Munich, Ludwig-Maximilians-Universität München, Munich, Germany
[b] Graduate School of Systemic Neurosciences, Ludwig-Maximilians-Universität München, Martinsried, Germany
[c] Division of Neurobiology, Department Biology II, Ludwig-Maximilians-Universität München, Martinsried, Germany

ARTICLE INFO

Article history:
Received 11 January 2017
Received in revised form
10 February 2017
Accepted 15 March 2017
Available online 18 March 2017

Keywords:
Galvanic vestibular stimulation
Zwicker tone
Tinnitus
Amplitude modulation
Bounce phenomenon
Electrical stimulation

ABSTRACT

Transcutaneous, electrical stimulation with electrodes placed on the mastoid processes represents a specific way to elicit vestibular reflexes in humans without active or passive subject movements, for which the term galvanic vestibular stimulation was coined. It has been suggested that galvanic vestibular stimulation mainly affects the vestibular periphery, but whether vestibular hair cells, vestibular afferents, or a combination of both are excited, is still a matter of debate. Galvanic vestibular stimulation has been in use since the late 18th century, but despite the long-known and well-documented effects on the vestibular system, reports of the effect of electrical stimulation on the adjacent cochlea or the ascending auditory pathway are surprisingly sparse.

The present study examines the effect of transcutaneous, electrical stimulation of the human auditory periphery employing evoked and spontaneous otoacoustic emissions and several psychoacoustic measures. In particular, level growth functions of distortion product otoacoustic emissions were recorded during electrical stimulation with alternating currents (2 Hz, 1–4 mA in 1 mA-steps). In addition, the level and frequency of spontaneous otoacoustic emissions were followed before, during, and after electrical stimulation (2 Hz, 1–4 mA). To explore the effect of electrical stimulation on the retrocochlear level (i.e. on the ascending auditory pathway beyond the cochlea), psychoacoustic experiments were carried out. Specifically, participants indicated whether electrical stimulation (4 Hz, 2 and 3 mA) induced amplitude modulations of the perception of a pure tone, and of auditory illusions after presentation of either an intense, low-frequency sound (Bounce tinnitus) or a faint band-stop noise (Zwicker tone).

These three psychoacoustic measures revealed significant perceived amplitude modulations during electrical stimulation in the majority of participants. However, no significant changes of evoked and spontaneous otoacoustic emissions could be detected during electrical stimulation relative to recordings without electrical stimulation.

The present findings show that cochlear function, as assessed with spontaneous and evoked otoacoustic emissions, is not affected by transcutaneous electrical stimulation, at the currents used in this study. Psychoacoustic measures like pure tone perception, but also auditory illusions, are affected by electrical stimulation. This indicates that activity of the retrocochlear ascending auditory pathway is modulated during transcutaneous electrical stimulation.

1. Introduction

In the late 18th century Alessandro Volta described the effects of electrical stimulation (ES) on the human body for the first time (Volta, 1800). During self-experimentation, Volta placed electrodes, connected to batteries, near his ear. He subsequently collapsed and experienced spinning and the acoustic sensation of an explosion

---

Abbreviations: AC, alternating current; DC, direct current; DPOAE, distortion product otoacoustic emission; ES, electrical stimulation; EEOAE, electrically evoked otoacoustic emission; GVS, galvanic vestibular stimulation; OAE, otoacoustic emission; OHC, outer hair cell; AM, amplitude modulation; SOAE, spontaneous otoacoustic emission

[*] Corresponding author.

E-mail address: markus.drexl@med.uni-muenchen.de (M. Drexl).

http://dx.doi.org/10.1016/j.heares.2017.03.008
0378-5955/© 2017 Elsevier B.V. All rights reserved.

inside his head (Volta, 1800). Nowadays, transcutaneous ES with electrodes placed on the mastoid processes, for which the term galvanic vestibular stimulation (GVS) was coined, is frequently used as a tool to probe vestibular function in humans without passive or active movements of the tested participants. GVS with direct current (DC) stimulation activates the vestibular system and causes a sway, which can be interpreted as the summed activity of the otolithic organs and the semicircular canals (Fitzpatrick and Day, 2004). It is still a matter of debate which parts of the vestibular system (vestibular hair cells and/or vestibular afferents) are specifically excited by GVS (Cohen et al., 2011, 2012; Curthoys and Macdougall, 2012; Wardman and Fitzpatrick, 2002).

Despite the long-known and well-documented activation of GVS on the vestibular system, reports on auditory percepts or on effects on the cochlea and the ascending auditory pathway are surprisingly sparse. During GVS, Bucher et al. (1998) showed activity in Heschl's gyrus containing the primary auditory cortex, but none of their subjects reported auditory sensations. High-frequency (0.5–20 kHz) ES of the mastoid in humans can result in auditory percepts, but this is due to an indirect, mechanical effect caused by tissue vibrations near the stimulation side which are consequently transmitted to, and detected by, the cochlea (Flottorp, 1976; Lopponen et al., 1991).

ES in general could affect the auditory system on several levels. This might include electrophonic activation of the basilar membrane, direct changes of hair cell receptor potentials, modulation of associated transmitter release, changes of spiral-ganglion-cell membrane potentials, and modulation of auditory-nerve spontaneous activity (Rubinstein and Tyler, 2004). A single previous study reported no changes of distortion-product otoacoustic emissions (DPOAEs) during ES (Cevette et al., 2012).

From animal experimentation, however, it is known that the cochlea indeed responds directly to ES: Electrically evoked otoacoustic emissions (EEOAEs) are sounds which can be recorded in the ear canal, when an alternating current (AC) stimulus excites the cochlea with electrodes typically placed on the round window membrane (e.g. Drexl et al., 2008; Ren and Nuttall, 1995, 2000; Ren et al., 1996). EEOAEs are thought to be generated by the electromechanical transduction of outer hair cells (OHCs) near the electrode location, driven by the external ES, and travel to the external ear canal with the same frequency as the electrical stimulus (Drexl et al., 2008; Ren and Nuttall, 1995; Ren et al., 1996; Ren et al., 2000; Zou et al., 2003). In addition, Frank and Kossl (1997) demonstrated that low-frequency (5 Hz) ES of the round window altered acoustically evoked otoacoustic emissions (OAEs).

In some human patients, extracochlear ES has been shown to suppress tinnitus, indicating that the activity of the retrocochlear auditory pathway can be modulated by ES (Cazals et al., 1978; Dobie et al., 1986; Kuk et al., 1989; Lyttkens et al., 1986; Portmann et al., 1979; Vernon and Fenwick, 1985).

Auditory illusions have been suggested as tinnitus models (Drexl et al., 2014; Hoke et al., 1996; Hoke et al., 1998; Norena et al., 2000; Patuzzi and Wareing, 2002) and might represent a convenient way to study the effect of ES in the absence of acoustic stimulation. The Zwicker tone is an auditory illusion lasting between 1 and 6 s after the presentation of band-stop noise and is perceived as a pure tone with a frequency within the spectral gap of the band-stop noise (Fastl, 1989; Lummis and Guttman, 1972; Zwicker, 1964). Another illusion, the Bounce tinnitus, is perceived after the offset of intense, rather low-frequency sound (Hirsh and Ward, 1952; Hughes, 1954; Patuzzi and Wareing, 2002). The Bounce tinnitus is accompanied by small hearing threshold fluctuation and stereotypic OAE level changes (Drexl et al., 2014; Kemp, 1986; Kemp and Brill, 2009; Kevanishvili et al., 2006; Kugler et al., 2014; Zwicker and Hesse, 1984). These transient effects are thought to be the result of a temporarily challenged cochlear homeostasis and are summarized under the term Bounce Phenomenon. The Bounce tinnitus, which can be of different tonal quality (Ueberfuhr et al., 2016), lasts for around 1.5 min and vanishes gradually (Drexl et al., 2014; Patuzzi and Wareing, 2002).

The aim of the current study was to dissect the specific effects of ES on different levels of auditory processing: On a peripheral level, the effect of ES on OHCs, due to their electromotile properties and their role in OAE generation, can directly be assessed by OAE recordings. On a retrocochlear level, the effects of ES on the perception of an externally presented pure tone were examined. Additionally, the influence of ES on two auditory illusions, in the absence of external acoustic stimulation, was explored with psychoacoustic measures.

2. Methods

2.1. Participants

Participants were eligible for this study when they had neither hearing problems nor tinnitus, and had not had any ear surgery or recent ear infection. All participants showed hearing thresholds of less than 25 dB HL between 0.25 and 8 kHz, tested with a Matlab-based automated procedure (Automatic Pure Tone Audiometry APTA-HF 2012 V2.28 (HörTech, Oldenburg, Germany)).

This study was approved by the Ethics Committee of the University Hospital Munich, Ludwig-Maximilians-Universität München, Germany, in agreement with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All participants gave their written informed consent. Experiments were conducted in a sound-attenuated booth at the Department of Biology, Ludwig-Maximilians-Universität München, Martinsried, Germany.

2.2. Signal generation and data acquisition

Signal generation and data acquisition was carried out with an RME Fireface UC 24-bit external sound card (RME, Audio AG, Haimhausen, Germany), operated with a sampling rate of 44.1 kHz. Scripts written in MatLab 7.5 (MathWorks, Natick, MA, USA) controlled the external sound card, employing the SoundMexPro sound application (HörTech, Oldenburg, Germany). The sound card forwarded commands to both the current stimulator for ES and to the sound systems for auditory stimulation. For OAE recordings, an ER-10C DPOAE probe system (Etymotic Research Inc., Elk Grove Village, IL) was used in one ear. In psychoacoustic experiments, both ears were exposed to sound and two different sound systems were used, the ER4 insert ear phones (Etymotic Research Inc., Elk Grove Village, IL) for the contralateral ear (here and in the following: the ear where a matching tone was presented) and the ER-10C DPOAE probe system for the ipsilateral ear (here and in the following: the ear where sounds were presented to induce an auditory percept or auditory illusions). To induce the Bounce tinnitus, an additional external loudspeaker (NSW1-205-8A, Aura Sound Inc., Santa Fe Springs, CA) driven by a power amplifier (RB-960BX, Rotel, Worthing, UK) was used to generate low-frequency sounds (30 Hz sine wave, 120 dB SPL, 90 s, including 0.1 s raised-cosine ramps). The loudspeaker was connected to a 50 cm long polyethylene tube (inner diameter 1 mm), the tip of which was fed through the foam ear tip of the ER-10C DPOAE probe. As the ER-10C probe contains a probe microphone for recording in the ear canal, ipsilaterally presented stimuli, including very low-frequency sounds, were calibrated in-situ. The magnitude response of the probe microphone at low frequencies is non-linear and was therefore compensated against the magnitude response of an artificial ear microphone (B&K 4157, Brüel & Kjær, Sound &