Available online at www.sciencedirect.com

ScienceDirect

Journal of Otology 11 (2016) 178−184

www.journals.elsevier.com/journal-of-otology/

Review

Intra-operative hearing monitoring methods in middle ear surgeries

Wei Ren[1], Fei Ji[1], Jialing Zeng, Hui Zhao*

Department of Otolaryngology/Head and Neck Surgery, Chinese PLA Institute of Otolaryngology, Chinese PLA General Hospital, 28 Fuxing Road, Beijing 100853, China

Received 19 September 2016; revised 28 December 2016; accepted 28 December 2016

Abstract

Hearing loss is a condition affecting millions of people worldwide. Conductive hearing loss (CHL) is mainly caused by middle ear diseases. The low frequency area is the pivotal part of speech frequencies and most frequently impaired in patients with CHL. Among various treatments of CHL, middle ear surgery is efficient to improve hearing. However, variable success rates and possible needs for prolonged revision surgery still frustrate both surgeons and patients. Nowadays, increasing numbers of researchers explore various methods to monitor the efficacy of ossicular reconstruction intraoperatively, including electrocochleography (ECochG), auditory brainstem response (ABR), auditory steady state response (ASSR), distortion product otoacoustic emissions (DPOAE), subjective whisper test, and optical coherence tomography (OCT). Here, we illustrate several methods used clinically by reviewing the literature.

Keywords: Intraoperative monitoring; Middle ear surgery; Hearing

Contents

Hearing loss is a worldwide condition affecting millions of people. It can be divided into conductive hearing loss (CHL) and sensorineural hearing loss (SNHL) according to its pathogenic mechanisms. CHL is mainly caused by middle ear diseases. Low-frequencies, which are the pivotal part of speech frequencies, are the frequencies mostly impaired in patients with CHL. Therefore, middle ear diseases can greatly affect patients' communication and speech understanding.

Among various therapies for CHL, middle ear surgery may be the most effective in improving hearing. It has been

* Corresponding author.
E-mail address: huizhao@yeah.com (H. Zhao).
Peer review under responsibility of PLA General Hospital Department of Otolaryngology Head and Neck Surgery.
[1] These authors contributed equally to this article.

http://dx.doi.org/10.1016/j.joto.2016.12.003

reported that nearly 69% patients with CHL can gain improved hearing and reduced air-bone gap (ABG) via ear surgeries (Shah et al., 2013). As general anesthesia replaces local anesthesia in most otologic surgeries nowadays, it is difficult to assess efficacy of ossicular reconstruction intraoperatively. Therefore, the uncertainty in surgery success rate and possibility of needing revision surgeries continue to frustrate surgeons as well as patients.

Therefore, increasing numbers of researchers and surgeons are exploring ways to monitor hearing results during ossicular reconstruction operations, including electrocochleography (ECochG), auditory brainstem responses (ABRs), auditory steady state responses (ASSRs), distortion product otoacoustic emissions (DPOAEs), subjective whisper test, and optical coherence tomography (OCT).

1. Auditory brainstem responses (ABRs)

ABRs are a series of electrical potentials recorded from scalp electrodes upon acoustic stimulation, generated from auditory pathways, including the auditory nerve and brainstem (Moller et al., 1981; Moller and Jannetta, 1981) during the first 10−20 ms after the onset of a transient stimulus. They were firstly described by Jewett et al. (1970) and soon became the most widely used objective audiometry clinically for its objective, replicable, and noninvasive nature. ABRs are essentially unaffected by the patient's cognitive conditions, such as sleep, sedation or attention. They have been used to monitor auditory function during otological and neurotological procedures, and gradually become the routine intraoperative monitoring method in cerebellopontine angle surgeries and acoustic neuroma surgeries to alert the surgeon of an impending damage to the peripheral auditory pathway. Initially, ABRs were applied intraoperatively jointly with simultaneous ECochG (Lambert and Ruth, 1988), but since then both ABRs and ECochG have been treated as possible independent alternatives. Selesnick suggested that intraoperative brainstem auditory evoked responses (BAERs) monitoring might be able to predict postoperative hearing improvement in patients undergoing ossicular reconstruction surgery intraoperatively (Selesnick et al., 1997). Thereafter, more research has reported using ABRs as an intraoperative monitoring tool in middle ear surgeries, especially in stapes surgeries. Hsu monitored immediate hearing change during stapedectomy to guide adjustment of prosthesis positions, suggesting that intraoperative ABR monitoring might be a promising tool to help improve postoperative hearing outcomes and reduce the need for revision (Hsu, 2011).

Although intraoperative ABR monitoring can work smoothly in the operation room, it has its own limitations:

1. The above researches chose clicks as the stimulus signal. Clicks are broadband noise without frequency specificity, with its energy concentrating between 2 and 4 kHz. Folsom found that click-ABRs mainly reflected high frequency hearing thresholds with limited information on lower-frequency hearing both in adults and infants (Werner et al., 1993). Bauch et al. later also demonstrated that click-ABR thresholds correlated well with high frequency (2, 4 and 8 kHz) pure tone audiometry (PTA) results, rather than low frequencies (Stapells and Oates, 1997; Martinez Ibarguen, 1993). More and more reports point out that click-ABRs are better at predicting sensorineural rather than conductive hearing loss (Abdala and Folsom, 1995), which may affect its accuracy and predicting value in intraoperative hearing assessment in patients with CHL.
2. Although ABRs have been perceived as an "objective" measurement of hearing, subjective judgement is involved in identifying recorded waveforms and determining response threshold. Therefore a professionally trained surgeon or audiologist would be needed to interpret the results during middle ear surgeries. Nowadays automated ABRs (AABRs) have become a universal test in newborn hearing screening, but a few reports have suggested that AABRs can also be used as a standard test in adults. Further research is needed to study if AABRs during ossicular reconstruction surgeries can improve the accuracy of intra-operative monitoring.
3. Insert earphones are used as the output transducer in ABR audiometry. Irrigation fluid, blood or serum can get into the external canal, causing additional/artificial conductive hearing loss and threshold shift intraoperatively and subsequently affecting monitoring accuracy and predicting values. Future research may try to replace insert earphones with loudspeakers to help improve test efficiency as well as better compliance to asepsis protocols intra-operatively.

2. Frequency-specific auditory brainstem responses (fsABRs)

Since broadband stimuli, such as clicks, tend to underestimate hearing loss (especially steep sloping hearing loss), frequency-specific auditory brainstem responses have attracted attention.

Generally, there are two ways to obtain frequency specificity. Some use frequency-specific acoustic signals as stimuli, for instance, tone bursts, filtered clicks, tone pips and chirps, among which tone bursts and tone pips are the most popular; others use masking and filtering techniques. Davis et al. in 1976 recommended to use the "2-1-2" signal cycle tone pip (Davis, 1976), which has been widely used to date.

Later, studies were conducted to explore the accuracy of frequency-specific ABRs. Stapell and Oates suggested that tonal ABRs could be recorded in most circumstances and could predict accurately behavioral thresholds in nearly all populations (Stapells and Oates, 1997). They later conducted a meta-analysis using nearly 30 studies in this field, including infants and adults with or without hearing loss, demonstrating good relationship between tone-pip ABR and behavioral thresholds, with averaged differences of +5.5 to −8.1 dB. Meanwhile, Schoonhoven reported a 15−18 dB difference between click ABR and behavioral thresholds in a hearing impairment population, and the presence of otitis media increased the difference to more than 25 dB (Schoonhoven et al., 2000). Various studies have suggested that frequency-specific ABRs are better correlated with the pure tone audiometry compared to click ABRs at octave frequencies from 500 to 8000 Hz no matter in infants or adults with or without hearing loss (Beattie et al., 1996; Canale et al., 2012; Vander Werff et al., 2009). These studies reported an average difference of 7—9.5 dB between frequency-specific ABRs and pure tone audiometry, much less than that of click ABRs. More recently, Stevens tested click and tone-pip ABRs in 94 babies referred by universal hearing screening to explore their accuracy in predicting hearing loss. He found that tone pip ABRs had a similar accuracy to that reported in adults and older children and that tone-pip ABRs were a much better predictor compared with click ABRs (Stevens et al., 2013).

Some researchers also studied the difference between frequency-specific ABRs and ASSRs in predicting hearing thresholds. Johnson and Brown made a within-subject comparison between the two methods in 14 subjects with or without hearing loss. He found that frequency-specific ABR thresholds were 3 dB closer to behavioral thresholds than ASSR thresholds, but in some subjects with steep sloping hearing loss, ASSRs seemed to be much more accurate (Johnson and Brown, 2005).

Knowing its frequency-specific nature, Canale et al. investigated the predicting value of tone burst ABRs at low frequencies in 56 subjects divided into three groups based on the pathogenic mechanism of their hearing loss. He recommended tone burst ABRs as a good predictor of hearing impairment in low frequencies, especially in populations with suspected hearing loss (Canale et al., 2012). Dagna studied the accuracy of different tone burst signals at 1 kHz in predicting thresholds, and suggested that thresholds tested using Blackman window stimuli were closer to the pure tone threshold, especially in the case of suspected hearing loss (Dagna et al., 2014). Liang at the PLA General Hospital also investigated the frequency specificity of tone pip stimuli at different frequencies. He also recommended Blackman gating and longer duration tone pips as the best signal. Detailed test parameters were given in the article. It seems that frequency-specific ABRs are a good predictor of hearing loss, especially in the hearing impaired population.

Thereafter, some studies tried to apply frequency-specific ABRs intraoperatively to monitor the hearing integrity. Pau used tone burst ABRs to monitor residual hearing in cochlear implant patients, suggesting it as a possible tool of intraoperative hearing assessment (Pau et al., 2008). Ren and Ji at the PLA General Hospital searched for an effective intraoperative monitoring technique that could be used under general anesthesia in the operation room. They used 1 kHz tone pip ABRs to assess hearing thresholds in normal subjects and in subjects with conductive hearing loss under general anesthesia, with comparison to their 1 kHz behavioral thresholds. Besides, they replaced insert earphones with loudspeakers to improve aseptic protocol compliance and stimulus intensity. They suggested that 1 kHz tone pip ABR testing might be an effective way to assess ossicular reconstruction efficacy intra-operatively (Ren et al., 2016).

It seems that frequency-specific ABRs may become a better intra-operative predictor and monitor of hearing thresholds in ossicular reconstruction surgeries. However, more studies are needed to optimize test parameters. Besides, the influence of background noise and electromagnetic interference caused by equipment in the operation room remain unpredictable, which may adversely affect accurate threshold measurement intra-operatively. Further studies are needed to resolve these problems.

3. Electrocochleography (ECochG)

ECochG is a commonly used near-field measurement of peripheral auditory function. The three main components of ECochG are cochlea microphonics (CM), summating potential (SP), and action potentials (AP). The former two reflect the cochlea bioelectric function and AP is generated by the synchronous firing of eighth nerve fibers and is equivalent to ABR wave I. With the development of extra-tympanic electrodes, ECochG has become non-invasive and is widely used in the diagnosis of certain diseases (such as endolymphatic hydrops and superior semicircular canal dehiscence syndrome) (Adams et al., 2011), hearing assessment and intraoperative monitoring of the eighth nerve and cochlea (Ruth et al., 1988).

ECochG can provide real-time information, enabling quick responses to changes of auditory nerve function. Furthermore, it presents relatively greater amplitudes than ABRs, making it easier to assess cochlear status. Thirdly, because of its more rapid feedback and higher signal to noise ratio than ABRs, in the operating room, it requires relatively short time to acquire a response. It is, therefore, perceived by many as surpassing ABRs as an intraoperative hearing measurement, faster, easier and more sensitive. Lambert and Ruth were among the first to supplement ABRs with simultaneous ECochG to monitor hearing pathways in the operating room in 1988 (Lambert and Ruth, 1988). Later, ECochG was gradually separated as a possible alternative, mainly used in cochlear implant (CI) (Wang et al., 2006; Calloway et al., 2014; McClellan et al., 2014), cerebellopontine angle (CPA) tumor resection (Morawski et al., 2007) (such as acoustic neuroma (AN) or vestibular schwannoma resection), superior semicircular canal dehiscence (SSCD) repair (Adams et al., 2011) and so on, to help protect function of the cochlea and monitor integrity of the eighth nerve.

Some researchers have tried to use ECochG as an intraoperative monitoring tool in middle ear surgeries. Höhmann suggested that it might become a promising tool to assess the function of reconstructed ossicular chain (Hohmann, 1992). Later, Wazen evaluated its effectiveness in CHL surgeries (Wazen, 1994). In his study, Wazen used intraoperative ECochG monitoring in stapedectomy and ossicular reconstruction, and demonstrated that ECochG could verify the functional integrity of reconstructed ossicles efficiently (Wazen et al., 1997). Researchers have also demonstrated its role in optimizing the position of floating mass transducer (FMT) of Vibrant Soundbridge on the round window membrane (Adams et al., 2011), but no corresponding criteria have been agreed upon for guiding FMT adjustment. However, trans-tympanic ECochG (TT-ECochG) was used in these studies, which could not correctly reflect acoustic transfer function of the reconstructed ossicular chain.

As an intraoperative testing tool, ECochG has its own pitfalls. Its reliability and validity have been questioned due to relatively long-time persistence of ECochG potentials after complete eighth nerve transection. Levine et al. once reported a maintained ECochG response for 80 days in a patient after the excision of an acoustic neuroma with no measurable hearing postoperatively (Levine et al., 1984). Silverstein et al. also reported a patient with persisting ECochG potentials for 25 min after a complete transection of eighth nerve (Silverstein et al., 1985). Symon et al. reported 2 of the 24 patients undergoing acoustic neuroma procedure with ECochG monitoring, who presented with a "normal" potential despite severe hearing loss (Symon et al., 1988). These reports led people to animal experiments. In 1962, Fisch and Ruben recorded persisted ECochG potentials when the eighth nerve was cut (Fisch and Ruben, 1962). Ruben et al. later reported that ECochG N1 and N2 potentials could exist for nearly 48 h after complete eighth nerve transection (Ruben et al., 1962). Wazen recorded ECochG while progressively cutting the eighth nerve in 12 cats. Six of the 11 ears (54%) showed remaining potentials, although with reduced amplitudes and prolonged latencies (Wazen, 1994). Rosahl et al. reported immediate disappearance of ABR waveforms after total sharp transection of the eighth nerve in adult rats. However, a positive potential similar to ABR wave Ia reappeared 2 weeks later. He suggested that early components of hearing monitoring modalities, such as ABRs and ECochG, could not be used to determine integrity of the auditory pathway (Rosahl et al., 2000). Actually, discrepancies between animal experiments and human experiences have long been noticed in the literature, and further studies are needed to test auditory assessment measures. From the above review, ECochG may work jointly with other methods to monitor hearing intraoperatively.

Besides, intra-operative ECochG is conducted without restoring the external canal flap and responses are recorded with an open middle ear, potentially causing overestimation of the hearing threshold.

Thirdly, like ABRs, the insert earphone may be blocked by blood or serum during monitoring, consequently causing additional conductive hearing loss and threshold shift (Pau et al., 2008). Actually, this is a problem faced by all hearing measurements using earplugs.

4. Auditory steady state responses (ASSRs)

ASSRs are an objective audiometry for uncooperative populations, for example, neonates, infants, uncooperative adults and cochlea implant patients (Rance et al., 1998; Cone-Wesson et al., 2002; Menard et al., 2004; Oghalai et al., 2009). Continuous and frequency specific sound stimuli can be used to assess hearing loss at a specific frequency (500, 1000, 2000, 4000 or 8000 Hz). An advantage is objective judgement of hearing thresholds without the need for subjective interpretation. Series of reports have demonstrated ASSRs' high level correlation with PTA thresholds at each frequency in the normal hearing population (Ahn et al., 2007; Beck et al., 2014). In subjects with hearing loss, average differences between PTA and ASSR thresholds at each frequency decrease as the severity of hearing loss increases, suggesting ASSRs as a more suitable assessment tool for hearing loss populations (Hosseinabadi and Jafarzadeh, 2015). Some even compared the accuracy of ABRs and ASSRs in measuring hearing loss. ABRs surpass ASSRs on average, but ASSRs seem to be more reliable in predicting auditory thresholds for hearing loss patients, especially those with steep sloping on audiograms (Johnson and Brown, 2005; Lin et al., 2009).

Because of these advantages, more and more researchers have investigated their utility in middle ear surgeries. On the several parameters associated to intraoperative ASSR monitoring, series of studies have been conducted. Firstly, the modulation rate in ASSR testing is crucial (Purcell and John, 2010; Rampp et al., 2016). It was reported that responses evoked by fast modulation rates (>70 Hz) were from brainstem and primary auditory cortices, whereas those evoked by slow modulation rates were from superposition of most major ABR waves (Herdman et al., 2002; Cebulla et al., 2012; Giani et al., 2012; Muhler, 2012). Rampp et al. applied ASSRs to monitoring auditory nerve function in 20 patients under total intravenous anesthesia. He recommended 90 and 110 Hz as suitable intraoperative ASSR monitoring parameters (Rampp et al., 2014). Secondly, various noises, including background EEG activities, electromagnetic noise from equipment and surrounding acoustic noises, may influence the recording. This is a common problem facing all intra-operative tests. Some researchers perceived ASSRs as the most anti-interference method (Verhaegen et al., 2010), others, like Rampp, suggested that characteristics of background noise should be analyzed first, for it would impact the modulation choice, detection efficiency, test time and most importantly, the error rate.

In 2010, Verhaegen used ASSRs to assess and determine optimal positions of the floating mass transducer (FMT) in 4 patients undergoing vibrant soundbridge implantation. After adjustment based on intra-operative test results, 13 dB hearing improvement was detected. He suggested that intraoperative ASSR monitoring could be a useful tool to help guide prosthesis placement in ossicular chain reconstruction surgeries (Verhaegen et al., 2010). He also noted that 15 dB improvement should be considered as statistically important for this method. However, this may be considered as of minor clinical importance, for this can be achieved by modifying the audioprocessor gain.

Besides, like the methods mentioned above, ASSRs are also time-consuming, averaging about 20 min. The upper limit of sound stimulus intensity is 70–80 dB nHL due to the nature of ASSRs.

5. Distortion product otoacoustic emissions (DPOAEs)

Otoacoustic emissions (OAEs) are noninvasive and objective measures to assess the function of cochlear outer hair cells. OAEs are produced by outer hair cells, from their biomechanical motility nature, and can be divided into spontaneous and evoked emissions. Clinically, distortion product otoacoustic emissions (DPOAEs) are used as a universal method to measure the function of outer hair cells.

Filipo et al. used DPOAEs to monitor hearing improvement in surgeries for otosclerosis. DPOAEs were detected only in 2 of the 15 patients in the study, with low amplitudes and a narrower frequency range. At 1 month after surgery, only 4 patients showed detectable DPOAE amplitudes, suggesting that DPAOEs may played only an auxiliary role in assessing hearing improvement intraoperatively. Therefore, DPOAEs may not be recommended as an intra-operative monitoring tool on their own (Filipo et al., 2007).

6. Whisper test

Previously, middle ear surgeries were conducted under local anesthesia, and intra-operative tuning fork test, whisper hearing test or pure tone test were done immediately after ossicular reconstruction. Jankowski et al. conducted whisper hearing tests 1 m away from patients undergoing stapedotomies (Teflon-piston procedure) immediately after the surgery. High proportions of patients reported hearing improvement, but patients showing PTA improvements in the following up were disproportional (Jankowski et al., 2010). This may be attributed to the following: a) patients had strong willingness of hearing improvement from the surgical treatment; and b) background noise interfered with the results. Thus, subjective hearing test may be affected by more factors than objective hearing evaluation. It seems that subjective methods are not suitable for intra-operative hearing assessment.

7. Other methods

Besides the auditory methods mentioned above, a few imaging technologies such as optical coherence tomography (OCT) have also been used in middle ear surgeries.

OCT is a non-invasive and non-contact method for imaging structures with a resolution of micrometres. Heermann et al. used OCT in stapedoplasty and tympanoplasty type III surgeries to help best determine the length and coupling position of the prosthesis. The study suggested that all subjects showed good auditory performances during the following up. He recommended OCT as an efficient tool to monitor surgery efficacy in ossiculoplasty (Heermann et al., 2002). Later, Just et al. bound the appliance to the microscope used in surgery. OCT was used to show the reconstructed middle ear and inner ear structures with or without congenital abnormalities intraoperatively to help the surgeon optimize the position of the prosthesis. However, this kind of method have only been used in animal experiments. The high resolution of OCT can precisely display the delicate structures of and middle and inner ear as well as the prosthesis to help guide the surgeon during the surgery (Just et al., 2009). OCT does provide us with visualization of the reconstructed ossicular chain, however it does not reflect the transfer function of the ossicular chain and does not help finding the best position for the prosthesis. Besides, the surgeon would receive extra radiation intraoperatively, which can harm the health of the surgeons.

8. Discussion

Intra-operative ABR, ASSR and ECochG monitoring can help adjust the position of the prosthesis and improve the efficacy of ossicular reconstruction surgeries. However, to better assess intra-operative monitoring in middle ear surgeries, following works may be needed:

Firstly, more suitable test parameters need to be determined. Since the transfer function of the reconstructed ossicular chain is our main focus, specific parameters should be defined to assess the transfer function.

Secondly, interference in the operation room needs to be minimized. Operating room contains numerous equipment necessary for the operation. Interference has been reported in various studies, mainly from background noise and magnetic disturbances caused by the equipment, which can make interpreting test results difficult and lead to erroneous estimate of hearing threshold (over- or underestimation). Therefore, further studies are needed to identify means to lower such interference.

Thirdly, criteria are needed to help determine appropriate placement of the prosthesis. Although a number of researchers have reported adjusting prosthesis position intraoperatively based on threshold test feedback, no guidelines or criteria have been proposed to guide the surgeon as to how the position should be adjusted.

Fourthly, the monitoring test time needs to be shortened. Undoubtedly, intra-operative monitoring is time-consuming, it can take approximately 20 min for ECochG as a real-time monitoring technique. Monitoring procedures need to be simplified, or maybe specific frequencies can be chosen to assess the average low-frequency threshold. This may greatly reduce the monitoring test time.

In conclusion, all methods discussed above have their own advantages and disadvantages. But it is clear that hearing monitoring can help improve middle ear surgery quality, reduce the rate of revision and optimize prosthesis position during ossicular reconstruction. Undoubtedly, more research is needed to optimize intra-operative auditory monitoring to help improve ossicular chain reconstruction outcomes and further improve patient quality of life.

Acknowledgement

This work was supported by grants from Provincial Natural Science Foundation of Hai Nan (No. 20168349), the Clinical Research Supporting Foundation of PLA General Hospital (2016FC-TSYS-1014) National Basic Research Program of China (973 Program) (No. 2012CB967900) and National Basic Research Program of China (973 Program) (No. 2011CBA01000).

References

Abdala, C., Folsom, R.C., 1995. The development of frequency resolution in humans as revealed by the auditory brain-stem response recorded with notched-noise masking. J. Acoust. Soc. Am. 98 (2 Pt 1), 921–930.

Adams, M.E., et al., 2011. Electrocochleography as a diagnostic and intraoperative adjunct in superior semicircular canal dehiscence syndrome. Otol. Neurotol. 32 (9), 1506–1512.

Ahn, J.H., et al., 2007. Comparing pure-tone audiometry and auditory steady state response for the measurement of hearing loss. Otolaryngol. Head. Neck Surg. 136 (6), 966–971.

Beattie, R.C., Garcia, E., Johnson, A., 1996. Frequency-specific auditory brainstem responses in adults with sensorineural hearing loss. Audiology 35 (4), 194–203.

Beck, R.M., et al., 2014. Comparative study between pure tone audiometry and auditory steady-state responses in normal hearing subjects. Braz J. Otorhinolaryngol. 80 (1), 35–40.

Calloway, N.H., et al., 2014. Intracochlear electrocochleography during cochlear implantation. Otol. Neurotol. 35 (8), 1451–1457.

Canale, A., et al., 2012. Relationship between pure tone audiometry and tone burst auditory brainstem response at low frequencies gated with Blackman window. Eur. Arch. Otorhinolaryngol. 269 (3), 781–785.

Cebulla, M., et al., 2012. Auditory brainstem response recording to multiple interleaved broadband chirps. Ear Hear 33 (4), 466–479.

Cone-Wesson, B., et al., 2002. The auditory steady-state response: full-term and premature neonates. J. Am. Acad. Audiol. 13 (5), 260–269.

Dagna, F., et al., 2014. Tone burst stimulus for auditory brainstem responses: prediction of hearing threshold at 1kHz. Auris Nasus Larynx 41 (1), 27–30.

Davis, H., 1976. Principles of electric response audiometry. Ann. Otol. Rhinol. Laryngol. 85 (suppl 28(3 Pt3)), 1–96.

Filipo, R., et al., 2007. Distortion product otoacoustic emissions in otosclerosis: intraoperative findings. Adv. Otorhinolaryngol. 65, 133–136.

Fisch, U.P., Ruben, R.J., 1962. Electrical acoustical response to click stimulation after section of the eighth nerve. Acta Otolaryngol. 54, 532–542.

Giani, A.S., et al., 2012. Steady-state responses in MEG demonstrate information integration within but not across the auditory and visual senses. Neuroimage 60 (2), 1478–1489.

Heermann, R., et al., 2002. Application of optical coherence tomography (OCT) in middle ear surgery. Laryngorhinootologie 81 (6), 400–405.

Herdman, A.T., et al., 2002. Intracerebral sources of human auditory steady-state responses. Brain Topogr. 15 (2), 69–86.

Hohmann, D., 1992. Intraoperative monitoring with transtympanic electrocochleography. HNO 40 (4), 133–139.

Hosseinabadi, R., Jafarzadeh, S., 2015. Auditory steady-state response thresholds in adults with conductive and mild to moderate sensorineural hearing loss. Iran. Red. Crescent Med. J. 17 (1), e18029.

Hsu, G.S., 2011. Improving hearing in stapedectomy with intraoperative auditory brainstem response. Otolaryngol. Head. Neck Surg. 144 (1), 60–63.

Jankowski, A., et al., 2010. Subjective intraoperative hearing self-assessment in patients after stapedotomy comparing to postoperative pure-tone audiometry. Otolaryngol. Pol. 64 (5), 296–298.

Jewett, D.L., Romano, M.N., Williston, J.S., 1970. Human auditory evoked potentials: possible brain stem components detected on the scalp. Science 167 (3924), 1517–1518.

Johnson, T.A., Brown, C.J., 2005. Threshold prediction using the auditory steady-state response and the tone burst auditory brain stem response: a within-subject comparison. Ear Hear 26 (6), 559–576.

Just, T., et al., 2009. Optical coherence tomography in middle ear surgery. HNO 57 (5), 421–427.

Lambert, P.R., Ruth, R.A., 1988. Simultaneous recording of noninvasive ECoG and ABR for use in intraoperative monitoring. Otolaryngol. Head. Neck Surg. 98 (6), 575–580.

Levine, R.A., et al., 1984. Monitoring auditory evoked potentials during acoustic neuroma surgery. Insights into the mechanism of the hearing loss. Ann. Otol. Rhinol. Laryngol. 93 (2 Pt 1), 116–123.

Lin, Y.H., Ho, H.C., Wu, H.P., 2009. Comparison of auditory steady-state responses and auditory brainstem responses in audiometric assessment of adults with sensorineural hearing loss. Auris Nasus Larynx 36 (2), 140–145.

Martinez Ibarguen, A., 1993. Correlation of auditory brainstem evoked potentials and pure tone audiometric thresholds. Acta Otorrinolaringol. Esp. 44 (3), 169–173.

McClellan, J.H., et al., 2014. Round window electrocochleography and speech perception outcomes in adult cochlear implant subjects: comparison with audiometric and biographical information. Otol. Neurotol. 35 (9), e245–e252.

Menard, M., et al., 2004. Auditory steady-state response evaluation of auditory thresholds in cochlear implant patients. Int. J. Audiol. 43 (Suppl 1), S39–S43.

Moller, A.R., Jannetta, P.J., 1981. Compound action potentials recorded intracranially from the auditory nerve in man. Exp. Neurol. 74 (3), 862–874.

Moller, A.R., Jannetta, P.J., Moller, M.B., 1981. Neural generators of brainstem evoked potentials. Results from human intracranial recordings. Ann. Otol. Rhinol. Laryngol. 90 (6 Pt 1), 591–596.

Morawski, K.F., et al., 2007. Intraoperative monitoring of hearing during cerebellopontine angle tumor surgery using transtympanic electrocochleography. Otol. Neurotol. 28 (4), 541–545.

Muhler, R., 2012. On the terminology of auditory steady-state responses. What differentiates steady-state and transient potentials? HNO 60 (5), 421–426.

Oghalai, J.S., et al., 2009. Intra-operative monitoring of cochlear function during cochlear implantation. Cochlear Implants Int. 10 (1), 1–18.

Pau, H.W., et al., 2008. Monitoring residual hearing during cochlear implantation by intra-operative brainstem audiometry. Auris Nasus Larynx 35 (2), 264–268.

Purcell, D.W., John, M.S., 2010. Evaluating the modulation transfer function of auditory steady state responses in the 65 Hz to 120 Hz range. Ear Hear 31 (5), 667–678.

Rampp, S., et al., 2014. Viability of intraoperative auditory steady state responses during intracranial surgery. J. Clin. Neurophysiol. 31 (4), 344–351.

Rampp, S., et al., 2016. Towards an optimal paradigm for intraoperative auditory nerve monitoring with auditory steady state responses. J. Clin. Monit. Comput.

Rance, G., et al., 1998. Steady-state evoked potential and behavioral hearing thresholds in a group of children with absent click-evoked auditory brain stem response. Ear Hear 19 (1), 48–61.

Ren, W., et al., 2016. Preliminary application of intra-operative hearing monitoring by tone pip ABR via loudspeakers. Acta Otolaryngol. 1–7.

Rosahl, S.K., et al., 2000. Acoustic evoked response following transection of the eighth nerve in the rat. Acta Neurochir. 142 (9), 1037–1045 (Wien).

Ruben, R.J., Hudson, W., Chiong, A., 1962. Anatomical and physiological effects of chronic section of the eighth nerve in cat. Acta Otolaryngol. 55, 473–484.

Ruth, R.A., Lambert, P.R., Ferraro, J.A., 1988. Electrocochleography: methods and clinical applications. Am. J. Otol. 9, 1–11.

Schoonhoven, R., et al., 2000. Long-term audiometric follow-up of click-evoked auditory brainstem response in hearing-impaired infants. Audiology 39 (3), 135–145.

Selesnick, S.H., et al., 1997. Predictive value of intraoperative brainstem auditory evoked responses in surgery for conductive hearing losses. Am. J. Otol. 18 (1), 2–9.

Shah, K.D., et al., 2013. The efficiency of titanium middle ear prosthesis in ossicular chain reconstruction: our experience. Indian J. Otolaryngol. Head. Neck Surg. 65 (4), 298–301.

Silverstein, H., et al., 1985. Retrolabyrinthine vestibular neurectomy with simultaneous monitoring of eighth nerve and brain stem auditory evoked potentials. Otolaryngol. Head. Neck Surg. 93 (6), 736–742.

Stapells, D.R., Oates, P., 1997. Estimation of the pure-tone audiogram by the auditory brainstem response: a review. Audiol. Neurootol 2 (5), 257–280.

Stevens, J., et al., 2013. Predictive value of hearing assessment by the auditory brainstem response following universal newborn hearing screening. Int. J. Audiol. 52 (7), 500–506.

Symon, L., et al., 1988. Intraoperative monitoring of the electrocochleogram and the preservation of hearing during acoustic neuroma excision. Acta Neurochir. Suppl. 42, 27–30 (Wien).

Vander Werff, K.R., Prieve, B.A., Georgantas, L.M., 2009. Infant air and bone conduction tone burst auditory brain stem responses for classification of hearing loss and the relationship to behavioral thresholds. Ear Hear 30 (3), 350−368.

Verhaegen, V.J., et al., 2010. Intraoperative auditory steady state response measurements during Vibrant Soundbridge middle ear implantation in patients with mixed hearing loss: preliminary results. Otol. Neurotol. 31 (9), 1365−1368.

Wang, L., Cao, K., Wang, Z., 2006. Use of intraoperative round window electrocochleography for assessment of cochlear implantation safety. Lin. Chuang Er Bi Yan Hou Ke Za Zhi 20 (18), 822−824.

Wazen, J.J., 1994. Intraoperative monitoring of auditory function: experimental observations and new applications. Laryngoscope 104 (4), 446−455.

Wazen, J.J., Emerson, R., Foyt, D., 1997. Intra-operative electrocochleography in stapedectomy and ossicular reconstruction. Am. J. Otol. 18 (6), 707−713.

Werner, L.A., Folsom, R.C., Mancl, L.R., 1993. The relationship between auditory brainstem response and behavioral thresholds in normal hearing infants and adults. Hear Res. 68 (1), 131−141.