

Normal Summating Potential to Tone Bursts Recorded from the Tympanic Membrane in Humans

John A. Ferraro*
Wendy L. Blackwell*
Sarah Jo Mediavilla†
Bradley S. Thedinger†

Abstract

The use of tone-burst stimuli for electrocochleography (ECoChG) may offer certain advantages over conventional broad-band clicks. Namely, the summating potential (SP) component can be examined at different frequencies and may be easier to define and measure. To apply these findings clinically, it would first be necessary to establish SP amplitudes as a function of tone-burst frequency in normal listeners. The purpose of the present study was to do this using the tympanic membrane (TM) as the primary ECoChG recording site. ECoChG was recorded from 20 normal ears. Stimuli included 500-, 1000-, 2000-, 4000-, and 8000-Hz tone bursts presented randomly at 90 dB nHL. Mean SP amplitudes at these frequencies were +0.19, +0.17, +0.08, +0.10, and +0.22 microvolts, respectively. Although mean amplitudes were slightly positive regarding baseline, individual amplitudes varied between -0.41 and +0.73 microvolts. This study offers additional evidence that the SP to tone bursts can be recorded from the TM. The normative data provided should be useful for extended studies involving clinical populations.

Key Words: Action potential (AP), electrocochleography (ECoChG), summating potential (SP), tone burst, tympanic membrane (TM)

Electrocochleography (ECoChG) continues to be a useful tool in the identification and monitoring of certain otologic disorders, especially Meniere's disease/endolymphatic hydrops. The components of the electrocochleogram (ECoChGm) routinely analyzed for these purposes include the cochlear summating potential (SP) and the compound action potential (AP) of the auditory nerve. It is now well documented that in suspected cases of endolymphatic hydrops, the ECoChGm evoked by broad-band clicks (BBCs) is often characterized by an amplitude-enlarged SP especially in comparison to the AP amplitude (e.g., Schmidt et al, 1974; Gibson et al, 1977; Moriuchi and

Kumagami, 1979; Morrison et al, 1980; Coats, 1981, 1986; Kitahara et al, 1981; Goin et al, 1982; Ferraro et al, 1983, 1985; Staller, 1986; Ferraro, 1988; Ruth et al, 1988).

The BBC has been the most popular stimulus for ECoChG, primarily because it produces a well-defined AP. The transient nature of the click, however, makes it less than an ideal stimulus for studying cochlear potentials such as the SP, which has a stimulus-dependent duration. Figure 1 illustrates a synthetic SP overlaid with a real AP to reflect the presumed temporal relationship between these components. When both components are recorded together, as is usually the case in clinical ECoChG, the click-evoked SP extends into the time frame of the AP. Thus, the SP of the combined waveform is abbreviated. To help overcome this problem, some investigators have begun using tone-burst stimuli in addition to BBCs for ECoChG (Dauman et al, 1988; Gibson, 1991). A potential advantage of using tone bursts

*Hearing and Speech Department, School of Allied Health, University of Kansas Medical Center, Kansas City, Kansas; and †Midwest Ear Institute, Kansas City, Missouri
Reprint requests: John A. Ferraro, Hearing and Speech Department, School of Allied Health, University of Kansas Medical Center, Kansas City, KS 66160-7605

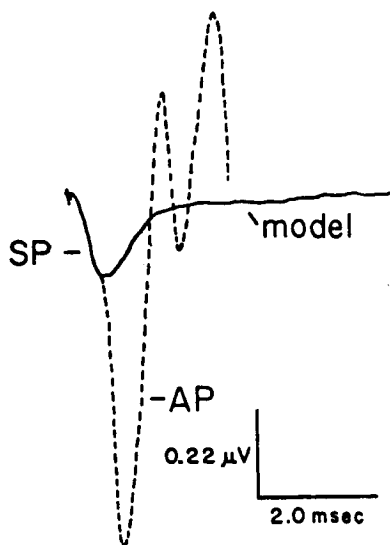


Figure 1 Synthetic summing potential (SP) overlaid with real action potential (AP) to reflect the presumed temporal relationship between the SP and AP when clicks are used as stimuli (from Durrant and Ferraro, 1991, p. 146).

is that the duration of the SP can be extended beyond that of the AP to allow for better definition of the former (i.e., the SP is no longer abbreviated). In addition, the SP to tone bursts can be examined at different frequencies.

Consistent with findings using BBCs, tone-burst-evoked SPs also display enlarged amplitudes in the presence of endolymphatic hydrops. For example, Gibson (1991) recorded SPs from the promontory in normal listeners, subjects with sensory hearing loss, and subjects with Meniere's disease using a 90-dB HL, 1000-Hz tone burst (2 msec rise/fall, 12 msec plateau). Mean, absolute SP amplitude for the normal subjects was only -0.4 microvolts. Mean SP amplitudes for the sensory hearing loss group were dependent on the degree of hearing loss, but were also noted to be very small (i.e., usually less than 1.0 microvolt). The Meniere's subjects, however, displayed mean SP amplitudes as large as -15.8 microvolts, once again depending on degree of hearing loss. Hohmann et al (1991) reported that tone-burst-evoked SPs from the promontory with negative amplitudes greater than 5 microvolts were pathognomonic of endolymphatic hydrops. Normative, frequency-specific SP amplitudes were not reported in this study.

The majority of ECochG studies using tone-burst stimuli have employed transtympanic (TT) recording techniques, wherein the primary electrode rests on the cochlear promontory. Al-

though the popularity of TT ECochG is beginning to mount, this method has not been well accepted in the United States, primarily because it is invasive. On the other hand, evidence from several laboratories supports the use of extratympanic (ET) methodology for routine ECochG applications, especially when the tympanic membrane (TM) is used as a recording site (Stypulkowski and Staller, 1987; Ruth et al, 1988; Ferraro and Ferguson, 1989). Levine et al (1992) and Margolis et al (1992) recorded SP from the TM to 1000-Hz tone bursts and BBCs in normal subjects and Meniere's patients. Both studies reported that the use of tone-burst stimuli enhanced the electrocochleographic evaluation of patients. As in Gibson's TT study (1991), however, results were reported only for responses to BBCs and 1000-Hz tone bursts. It may be the case that examination of the SP at additional frequencies would further enhance the evaluation. To examine this possibility, it would first be necessary to define normal SP amplitudes for a range of tone-burst frequencies.

The primary purpose of the present study was to determine SP amplitudes as a function of tone-burst frequency for normally hearing individuals, using the TM as the primary ECochG recording site. The stimulus frequencies used were 500, 1000, 2000, 4000, and 8000 Hz. Our intent was to provide normative data for extended studies and applications involving clinical populations.

METHOD

TM ECochG was recorded from 20 adult ears with normal hearing sensitivity and normal middle ear function. Pure-tone thresholds were better than 20 dB HL for all audiometric frequencies and there was no history of otologic disorders.

The TM electrode was a modification of the device described by Stypulkowski and Staller (1987) and virtually identical to the "tymptrode" described by Ferraro and Ferguson (1989). An operating microscope was used to confirm placement of the tymptrode tip on the TM. The electrode was held in place by the foam, EAR tip of the insert transducer used to deliver the stimulus to the ear. Figure 2 illustrates this arrangement.

Electrode configuration was TM(+)-to-ipsilateral earlobe(-) with ground at the contralateral earlobe. With BBC stimuli, we normally use a TM-to-contralateral earlobe configuration to maximize response amplitudes.

For tone-burst ECochG, however, an ipsilateral reference was used to inhibit components of the auditory brainstem response from appearing in the tracing and distorting the amplitude of the SP trough.

Acoustic stimuli were tone bursts with a 2-msec linear rise/fall time and a 10-msec plateau. Stimulus repetition rate was 5.3/sec. Tone-burst frequencies were presented randomly and included 500, 1000, 2000, 4000, and 8000 Hz. Intensity was held constant at 90 dB nHL, except at 8000 Hz, where the maximum output of our stimulus generator was limited to 75 dB nHL. Stimuli were delivered via an insert, tubal transducer (EAR Tone 3A) and in alternating polarity to inhibit the appearance of cochlear microphonic (CM) and stimulus artifact. Responses to 90 dB nHL BBCs (100- μ sec electrical pulses) presented at a rate of 11.3/sec were also obtained.

All recordings were made using a Nicolet Compact IV auditory evoked potential unit. The electrophysiologic response was amplified (50,000x) and filtered (10–3000 Hz, 12 dB/octave) prior to signal averaging. The recording window was 20 msec and 1000 samples were averaged. All tracings were repeated and hard copied for subsequent measurement.

SP amplitude was measured in the manner described by Gibson (1991). This involved defining the midpoint of the SP duration and comparing the amplitude at this point to a baseline amplitude. SP amplitude was measured at midpoint primarily to avoid the influence of the AP component, which appeared at the onset of the response. In addition, we were attempting to record both alternating- (AC) and direct-current (DC) potentials together (the AP and SP,

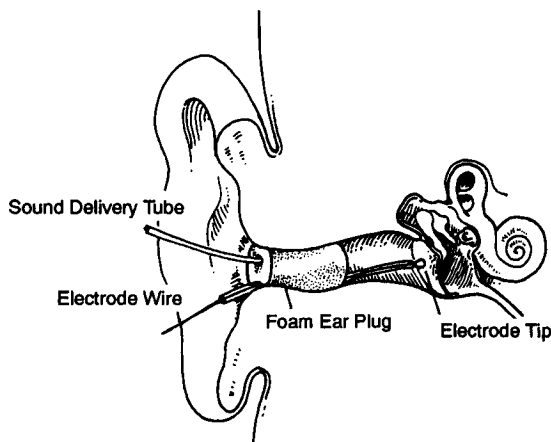


Figure 2 Illustration of tympanic membrane recording assembly (from Ferraro, 1992, p. 28).

respectively) using amplifiers designed primarily for AC voltages. This is a concern we have called attention to before (e.g., Ferraro et al, 1983), because it contributes to distortion of the DC component. Although this distortion is relatively minimal when the SP is recorded to brief transients (and thus is not a true DC potential), the effects are more pronounced when longer-duration stimuli such as tone bursts are used. In particular, the amplitude of the DC component will decay as a function of the time constant of the high-pass filter (which varies with frequency) and the duration of the voltage. Thus, measuring the SP amplitude at midpoint represented a compromise between avoiding the influence of the AP at onset and maximum decay of the SP at offset. In the present study, the specific SP amplitude at each frequency for a given subject represented the mean amplitude of two repeat tracings.

RESULTS

Figure 3 displays a normal TM-ECochG waveform to a 2000-Hz tone burst. The AP and its first negative peak, N_1 , appear at the onset of the SP. Because the duration of the SP is dependent on the duration of the stimulus envelope (2-msec rise time + 10-msec plateau + 2-msec fall time = 14 msec), we no longer see an SP "shoulder" preceding the AP as we do for BBC stimuli. Instead, the SP is represented as more of a "trough" lasting approximately 14 msec. SP amplitude was determined as the difference between the voltage at the midpoint (i.e., 7 msec) of the trough (point B) and a baseline voltage immediately preceding stimulus onset (point A). Definition of SP polarity was

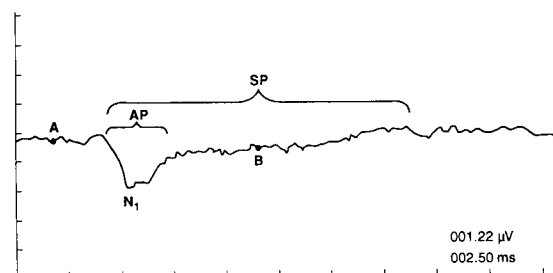


Figure 3 Normal electrocochleogram from the TM to a 2000-Hz tone burst. Action potential (AP) and its first negative peak (N_1) are seen at the onset of the summating potential (SP). SP duration defined by the upper bracket. SP amplitude measured at point B, with reference to point A. Amplitude (μ V) time (msec) scale at lower right.

based on whether the voltage at point B was + or - regarding the voltage level at point A. The amplitude (and thus polarity) of the SP in Figure 3, for example, was slightly negative.

Figure 4 displays the series of recordings obtained from a representative subject to illustrate the response patterns observed at each tone-burst frequency. Stimulus frequency (in kHz) is indicated to the right of each tracing and repeat waveforms (which virtually overlapped) have been omitted for the sake of simplicity. The sinusoidal-like pattern seen in the 0.5 kHz tracing in Figure 4 is probably phase-locked AP (Eggermont, 1991). Also of note is that the latency and amplitude of the AP-N₁ vary, as expected, with frequency. N₁ latency gets shorter as frequency is increased, reflecting, in part, cochlear travel time. AP amplitude generally grows smaller as frequency is reduced, because fewer synchronous discharges are contributing to the summed response. The AP component at 8 kHz is later and smaller than the APs at 1, 2, and 4 kHz, because the maximum output of our stimulus generator was limited to 75 dB nHL at 8 kHz.

Table 1 displays the SP amplitudes at each frequency for each of the 20 ears tested. Results (subjects) are listed in ascending order, beginning with the ear displaying the most negative amplitudes across frequencies. As can be seen from these data, TM-SP amplitudes were very small, rarely exceeding 0.5 microvolts at any frequency. Several values, in fact, were less than 0.00 microvolts. The largest negative amplitude was -0.41 microvolts at 4000 Hz (subject 1), whereas subject 20 displayed the largest positive amplitude of +0.73 microvolts at 8000 Hz. Mean amplitudes across subjects for each frequency and standard deviations are shown at

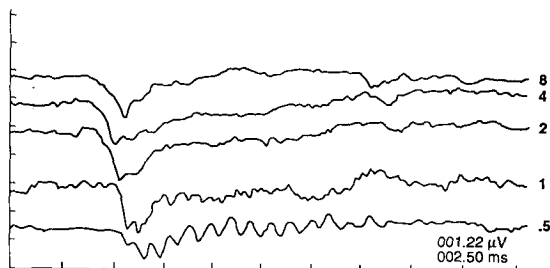


Figure 4 Series of TM-EcochG waveforms evoked by tone-burst stimuli from a representative subject. Tone-burst frequency (in kHz) indicated to the right of each waveform. Amplitude (μV)/time (msec) scale at lower right.

Table 1 SP Amplitudes* by Frequency for 20 Normal Ears

Subject	Frequency (Hz)				
	500	1000	2000	4000	8000
1	-.17	-.19	-.34	-.41	-.04
2	-.04	-.09	-.24	-.19	-.03
3	-.02	.04	-.14	-.14	.00
4	.00	.04	-.07	-.09	.00
5	.00	.04	-.07	.00	.00
6	.00	.07	.00	.00	.04
7	.04	.09	.00	.00	.04
8	.04	.09	.00	.00	.14
9	.09	.09	.00	.04	.19
10	.09	.12	.04	.04	.19
11	.09	.14	.04	.07	.21
12	.24	.14	.04	.19	.21
13	.26	.14	.12	.19	.21
14	.34	.21	.12	.21	.24
15	.34	.24	.19	.21	.29
16	.39	.34	.24	.29	.31
17	.41	.36	.26	.34	.43
18	.48	.46	.34	.34	.51
19	.48	.51	.48	.36	.68
20	.68	.53	.58	.53	.73
Mean	.19	.17	.08	.10	.22
SD	.22	.18	.22	.22	.22

*Amplitudes in microvolts and listed in ascending order, beginning with the subject displaying the most negative amplitudes across frequencies.

the bottom of Table 1 and displayed graphically in Figure 5.

Although mean SP amplitudes across subjects were positive regarding baseline at all frequencies, individual SPs may be positive or negative. It was clearly the case, however, that the majority of recordings displayed slightly positive SPs. In addition, SP polarity rarely varied between + and - across frequencies for a given subject. Although standard deviations were very similar across frequencies, variability among SP amplitudes across subjects at each frequency was as large as or exceeded the mean amplitude value for that frequency. Large amplitude variations are not uncommon for ET ECoG recordings, because of the inherent variability in signal-to-noise ratio associated with this approach.

DISCUSSION

The SP is a complex phenomenon, the amplitude and polarity of which will vary not only with frequency and intensity, but also with the position of the recording electrode (Dallos et

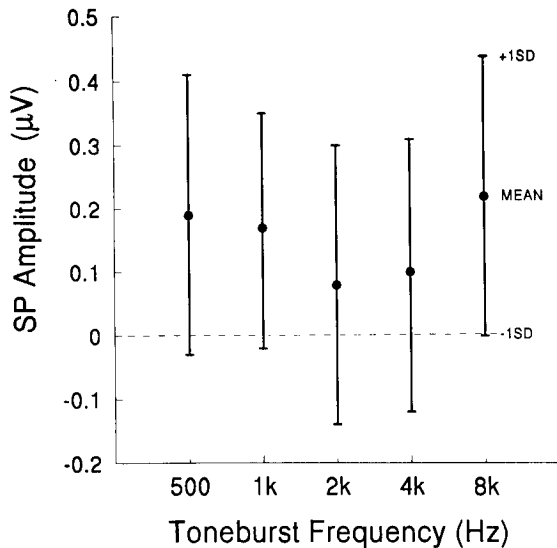


Figure 5 Mean summating potential (SP) amplitudes as a function of tone-burst frequency for 20 normal ears. Bars indicate ± 1 standard deviation (SD).

al, 1972; Eggermont and Odenthal, 1974; Eggermont, 1976; Schmidt et al, 1974). Electrode position may also account for the variations in SP polarity we observed in our normal subjects. Eggermont (1976), for example, observed SP polarity reversals in promontory recordings accompanying slight changes in electrode position. Van Deelen and Smoorenburg (1986) examined ECochG to tone bursts (1, 2, and 4 kHz) from three extracochlear sites in the guinea pig: near the round window, between the second and third turns, and at the apex. The most negative SP was always recorded at the surface of the apex, regardless of frequency. As the electrode was moved towards the basal turn, the negative SP became smaller, and the majority of SPs recorded from near the round window displayed positive amplitudes. Although extracochlear ECochG recordings in humans and guinea pigs are not directly comparable, the above study served to further illustrate the lability of SP polarity as electrode position is changed.

Given the above findings, it is reasonable to assume that even minor variations in the location of the electrode on the TM may account for the slight SP deviations above and below baseline we observed in our normal subjects. The clinical relevance of this characteristic, however, is questionable. That is, it appears from our findings that a normal, tone-burst-evoked SP may be slightly negative or positive when recorded from the TM. The range of amplitudes from most positive to most negative across

normal ears was approximately 1 microvolt. Thus, a TM-SP amplitude at any frequency exceeding this range might be considered abnormal. Indeed, we have measured SP amplitudes greater than 1 microvolt from Meniere's patients, and the polarities of these enlarged SPs always were negative. We have not yet examined, however, the effects of such aspects as type and degree of hearing loss on TM-SP amplitudes to tone bursts in Meniere's versus nonMeniere's subjects. Because hearing status has been shown to influence the SP amplitude (Gibson, 1991), a blanket statement regarding the limits of SP normalcy in the Meniere's population is premature at this time. In addition, it may be the case, given the magnitude of the standard deviations seen with TM recordings, that classification of the SP to tone bursts as normal/abnormal should be based on using an individual ear as its own control or between ear measures of the same patient. Further research with clinical populations is needed to assess this aspect.

The most utilized aspect of the ECochGm for clinical purposes has been the SP/AP amplitude ratio, primarily because of its repeatability in comparison to the absolute amplitudes of each component. When tone bursts are used, the rationale for using the SP/AP ratio becomes questionable. That is, when stimulus intensity and envelope are held constant, the amplitude of the AP will vary with frequency, as discussed earlier. In addition, and as can be seen in Figure 4, the AP component at 1000 Hz, and especially at 500 Hz, may be poorly defined.

Perhaps a more logical approach to examining the relationship between the SP and AP would be to do so utilizing stimuli conducive to evoking each component — that is, to make comparisons between the amplitudes of the tone-burst-evoked SP (SP_c) and the BBC-evoked AP (AP_c). Figure 6 represents the mean SP_c/AP_c amplitude ratios as a function of frequency for our normal subjects. Individual ratios may be + or -, depending on the polarity of the SP. Once again, however, mean values were slightly positive across frequencies. The largest mean SP_c/AP_c amplitude ratios of 0.16, 0.15, and 0.14 were observed at 8000, 500, and 1000 Hz, respectively, whereas the smallest ratios were seen at 2000 and 4000 Hz (0.06 and 0.08, respectively). These values were all smaller than the mean SP/AP amplitude ratio to BBCs in these subjects (0.29), which probably reflects the influence of uncanceled CM in the BBC-evoked responses. Another factor that may have con-

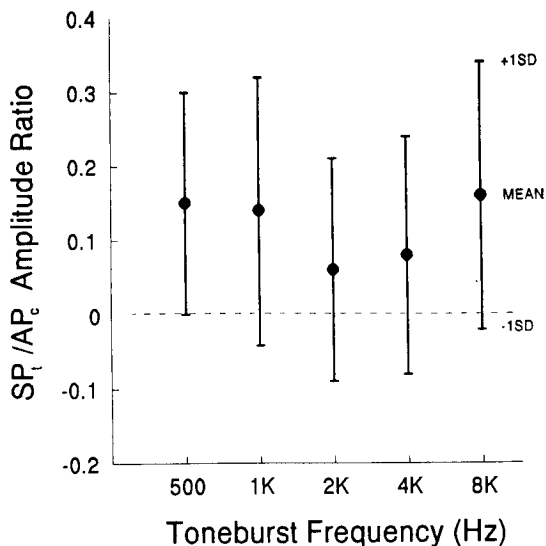


Figure 6 Mean summating potential to tone-burst (SP_t)/action potential to clicks (AP_c) amplitude ratios as a function of tone-burst frequency for 20 normal ears. Bars indicate ±1 standard deviation (SD).

tributed to a smaller SP/AP_c ratio is the decay of the SP amplitude to tone bursts attributable to AC filtering of a DC response (discussed earlier). The SP to brief transients (i.e., BBCs) is more tolerant of, and thus less affected by, filtering (Durrant and Ferraro, 1991). Lowering the high-pass cut-off frequency of the filter would mitigate this decay, but would also compromise clinical utility by raising the noise floor.

In summary, this study provides additional evidence that the SP to tone-burst stimuli can be recorded noninvasively from the TM. Tone-burst stimuli did indeed allow us to extend the duration of the SP beyond that of the AP to view the SP in an unabbreviated form. In addition, SP patterns (i.e., amplitude and polarity) did vary with frequency. Whether or not these features can be used to enhance the clinical utility of ECoChG, however, remains to be seen. The data presented should be useful in extended research of this nature, and also for comparative studies of ECoChG recording techniques.

Acknowledgment. Portions of this study were presented at the Biennial Meeting of the International Electric Response Audiometry Study Group, Terme de Comano, Italy, September, 1991.

REFERENCES

Coats AC. (1981). The summating potential and Meniere's disease. *Arch Otolaryngol* 104:199-208.

Coats AC. (1986). Electrocochleography: recording technique and clinical applications. *Semin Hear* 7:247-266.

Dallos P, Schoeny ZG, Cheatham MA. (1972). Cochlear summing potentials: descriptive aspects. *Acta Otolaryngol Suppl* 301:1-46.

Dauman R, Aran JM, Charlet de Sauvage R, Portmann M. (1988). Clinical significance of the summing potential in Meniere's disease. *Am J Otol* 9:31-38.

Durrant JD, Ferraro JA. (1991). Analog model of human click-elicited SP and effects of high-pass filtering. *Ear Hear* 12:144-148.

Eggermont JJ. (1976). Summing potentials in electrocochleography: relation to hearing disorders. In: Ruben RJ, Elberling C, Salomon G, eds. *Electrocochleography*. Baltimore:University Park Press, 67-87.

Eggermont JJ. (1991). Personal communication.

Eggermont JJ, Odenthal DW. (1974). Methods in electrocochleography. *Acta Otolaryngol Suppl* 316:7-16.

Ferraro JA. (1988). Electrocochleography. In: Owen JH, Donohoe CD, eds. *Clinical Atlas of Auditory Evoked Potentials*. Orlando, FL: Grune & Stratton, 1-14.

Ferraro JA. (1992). Electrocochleography: how - part I. *Aud Today* 4:26-28.

Ferraro JA, Best LG, Arenberg IK. (1983). The use of electrocochleography in the diagnosis, assessment and monitoring of endolymphatic hydrops. *Otolaryngol Clin North Am* 16:69-82.

Ferraro JA, Arenberg IK, Hassanein RS. (1985). Electrocochleography and symptoms of inner ear dysfunction. *Arch Otolaryngol* 111:71-74.

Ferraro JA, Ferguson R. (1989). Tympanic ECoChG and conventional ABR: a combined approach for the identification of wave I and the I-V interwave interval. *Ear Hear* 10:161-166.

Gibson WPR. (1991). Electrocochleography: a comparison of clicks versus tone bursts in the diagnosis of endolymphatic hydrops. *Proceedings of the Third International Symposium and Workshops on the Surgery of the Inner Ear*. Amsterdam/New York: Kugler Publications, 281-285.

Gibson WPR, Moffat DA, Ramsden RT. (1977). Clinical electrocochleography in the diagnosis and management of Meniere's disorder. *Audiology* 16:389-401.

Goin DW, Staller SJ, Asher DL, Mischke RE. (1982). Summing potential in Meniere's disease. *Laryngoscope* 92:1381-1389.

Hohmann DH, Gibson WPR, Arenberg IK, Dauman R, Bohlen HKH. (1991). International standards of trans-tympanic electrocochleography recordings. *Proceedings of the Third International Symposium and Workshops on the Surgery of the Inner Ear*. Amsterdam/New York: Kugler Publications, 249-252.

Kitahara M, Takeda T, Yazama T. (1981). Electrocochleography in the diagnosis of Meniere's disease. In: Volsteen KH, ed. *Meniere's disease, pathogenesis, diagnosis and treatment*. New York: Thieme-Stratton, 163-169.

Levine SC, Margolis RH, Fournier MA, Winzenburg BA. (1992). Tympanic electrocochleography for evaluation of endolymphatic hydrops. *Laryngoscope* 102:614-622.

- Margolis RH, Levine SC, Fournier EM, Hunter LL, Smith SL, Lilly DJ. (1992). Tympanic electrocochleography: normal and abnormal patterns of response. *Audiology* 31:8-24.
- Moriuchi H, Kumagami H. (1979). Changes of AP, SP and CM in experimental endolymphatic hydrops. *Audiology* 22:258-260.
- Morrison AW, Moffat DA, O'Connor AF. (1980). Clinical usefulness of electrocochleography in Meniere's disease: an analysis of dehydrating agents. *Otolaryngol Clin North Am* 11:703-721.
- Ruth RA, Lambert P, Ferraro JA. (1988). Comparison of tympanic membrane to promontory electrode recordings of electrocochleographic responses in Meniere's disease. *Otolaryngol Head Neck Surg* 100:546-552.
- Schmidt P, Eggermont JJ, Odenthal D. (1974). Study of Meniere's disease by electrocochleography. *Acta Otolaryngol Suppl* 316:75-84
- Staller SJ. (1986). Electrocochleography in the diagnosis and management of Meniere's disease. *Semin Hear* 7: 267-277.
- Stypulkowski PH, Staller SJ. (1987). Clinical evaluation of a new ECOG recording electrode. *Ear Hear* 8:304-310.
- van Deelen GW, Smoorenburg GF. (1986). Electrocochleography for different electrode positions in Guinea pig. *Acta Otolaryngol* 101:207-216.