SIGNAL PROCESSING APPROACHES ON OTOACOUSTIC EMISSIONS

by

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Abstract

The recent achievement on the measurement of otoacoustic emissions (OAEs) is based on a novel technical development of digital signal processing. OAEs measured in the external ear canal are normal by-products of the active process in hearing, which was discovered by Kemp (1978). Outer hair cells (OHCs) are thought to be the active source in the generation of this energy. Signal processing methods play a crucial role in the detection of OAEs in noise and artifacts, and in the extraction of information from OAE recordings. The present thesis is focused on the signal processing methods used in the recording, data representation, and information extraction of OAEs:

(1). A time-frequency method for analysis of transient evoked OAEs (TEOAEs) via smoothed pseudo Wigner distribution has been developed. TEOAEs can be transformed into the time-frequency plane to give a three-dimensional pattern. The analysis of shape and localization of TEOAE pattern and the comparison of pattern differences establish a method to extract more information from TEOAEs.

(2). An optimal recording protocol based on time-frequency analysis of TEOAEs has been proposed for neonatal hearing screening. A better signal-to-noise ratio (SNR) and a lower noise level of TEOAEs have been achieved by shortening the recording window and by using a linear recording protocol. The method has been applied in three audiological clinics in Europe. Time-frequency analysis of TEOAEs indicates a significantly reduced energy in the mid to high frequency bands for subjects with sensorineural hearing loss (SNHL) compared to normal-hearing subjects.

(3). TEOAEs, spontaneous OAEs (SOAEs) and distortion-product OAEs (DPOAEs) are related. The contribution from synchronized SOAEs to TEOAEs was demonstrated. The female and right ear advantages on OAEs were observed.

(4). Spectral estimation of SOAEs was performed by an average periodogram, a reduced variance estimate, and a model based high-order autoregressive (AR) estimate. Different spectral estimation methods can give more information on the spectral pattern of SOAEs.

(5). Active cochlear nonlinearity was estimated by multi-component DPOAEs and by introducing generating models of DPOAEs. The input-output function of the active cochlear nonlinearity was calculated from the multi-component DPOAEs. The results show that the generating mechanism of DPOAEs is dependent on stimulus level.

(6). The "bounce" phenomenon on basilar membrane nonlinearity was observed after exposure to a loud, but not traumatic low-frequency tone. This may give objective information on an individual's ability to recover from a temporal threshold shift (TTS).

In summary, the importance of these results relies mainly on the refinements of the measurement tools created, which can be used to investigate the function of the inner ear, especially the outer hair cells (OHCs).

Keywords: Otoacoustic emissions, signal processing, time-frequency representation, cochlea, outer hair cell, neonatal hearing screening, basilar membrane nonlinearity, "bounce" phenomenon, spectral estimation, interrelations of OAEs.

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To my parents and my family

This thesis is based on the following publications, referred to in the text by their Roman numerals:

I. **Cheng, J.** (1995). ”Time-frequency analysis of transient evoked otoacoustic emissions via smoothed pseudo Wigner distribution”, Scand. Audiol., 24, 91-96.

II. Hatzopoulos, S., **Cheng, J.**, Grzanka, A., Morlet, T., and Martini, A. (2000). ”Optimization of TEOAE recording protocols -- a linear protocol derived from parameters of a time-frequency analysis: a pilot study on neonatal subjects”, Scand. Audiol., 29, 21-27.

III. Hatzopoulos, S., **Cheng, J.**, Grzanka, A., and Martini, A. (2000). ”Time-frequency analyses of TEOAE recordings from normals and SNHL patients”, Audiology, 39, 1-12.

IV. **Cheng, J.** (1998). ”Otoacoustic emissions: Measurement, data and interrelations”, Acustica - acta acustica, 84, 320-328.

V. **Cheng, J.** (1998). ”Spectral estimation of spontaneous otoacoustic emissions”, Acustica - acta acustica, 84, 712-719.

VI. **Cheng, J.** (1999). ”Estimation of active cochlear nonlinearity by multi-component distortion-product otoacoustic emissions”, Acustica - acta acustica, 85, 721-727.

VII. **Cheng, J.** (2000). ”Quantifying basilar membrane nonlinearity and the 'bounce' phenomenon on the nonlinearity estimated by multi-component DPOAEs”, manuscript.

CONTENTS

ABBREVIATIONS

ABR	auditory brainstem response
ANOVA	analysis of variance
AR	autoregressive
ARMA	autoregressive moving average
BT method	Blackman and Tukey method
CF	characteristic frequency
CM	cochlear microphonic
COCB	crossed olivo-cochlear bundle
dB	decibel
DPOAEs	distortion-product otoacoustic emissions
FFT	fast Fourier transform
GM	geometric mean
HL	hearing level
IEC	International Electrotechnical Commission
IHC	inner hair cell
ILO	Institute of Laryngology and Otology (OAE instrument type)
MA	moving average
MLS	maximum length sequence
NIHL	noise-induced hearing loss
OAEs	otoacoustic emissions
OHC	outer hair cell
PBT	pseudo Blackman-Tukey spectrum
p.e.SPL	peak-equivalent sound-pressure level
PTA	pure-tone average
PTC	psychoacoustical tuning curve
PTS	permanent threshold shift
SFOAEs	stimulus-frequency OAEs
SL	sensation level
SNHL	sensorineural hearing loss
SNR	signal-to-noise ratio
SOAEs	spontaneous otoacoustic emissions
SPL	sound pressure level
SPWD	smoothed pseudo Wigner distribution
STFT	short-time Fourier transform
TEOAEs	transient evoked otoacoustic emissions
TFR	time-frequency representation
TTS	temporary threshold shift
WD	Wigner distribution
WT	wavelet transform

INTRODUCTION

The recent achievement on the measurement of otoacoustic emissions (OAEs) is based on the novel technical development of digital signal processing. OAEs measured in the external ear canal are normal by-products of the active process in hearing, which was discovered by Kemp (1978). Outer hair cells (OHCs) are thought to be the active source in the generation of this energy. Signal processing methods play a crucial role in the estimation of OAEs in the presence of noise and artifacts, and in extracting information from OAE recordings. This study is focused on the signal processing methods used in the recording of OAEs, signal representation of OAEs and information extraction from recorded OAE responses. The methods can be used to investigate the function of the cochlea, especially the OHCs.

The cochlea

The inner ear, also called the labyrinth, contains the organs of hearing and equilibrium. The bony labyrinth, a cavity in the temporal bone, is divided into three sections: the vestibule, the semicircular canals, and the cochlea. The cochlea is the only part of the inner ear involved in the hearing i.e. the perception of sound. The cochlea is a fluid filled tunnel organ, which is the part of inner ear that converts acoustic signals to the neural code that conveys auditory information to the brain. When the air pressure in front of the eardrum (tympanic membrane) increases, the eardrum is pushed inward, moving the three small bones of the middle ear: the malleus, incus and stapes. The footplate of the stapes covers the oval window of the cochlea, and the movement of the stapes initiates a pressure wave, which propagates along the cochlear partition (see Figure 1). This partition spans the width and length of the cochlea and consists of the basilar membrane, and Reissner's membrane with the organ of Corti and the stria vascularis. The length of the cochlear partition is about 35 mm and has two and a half turns for the human cochlea.

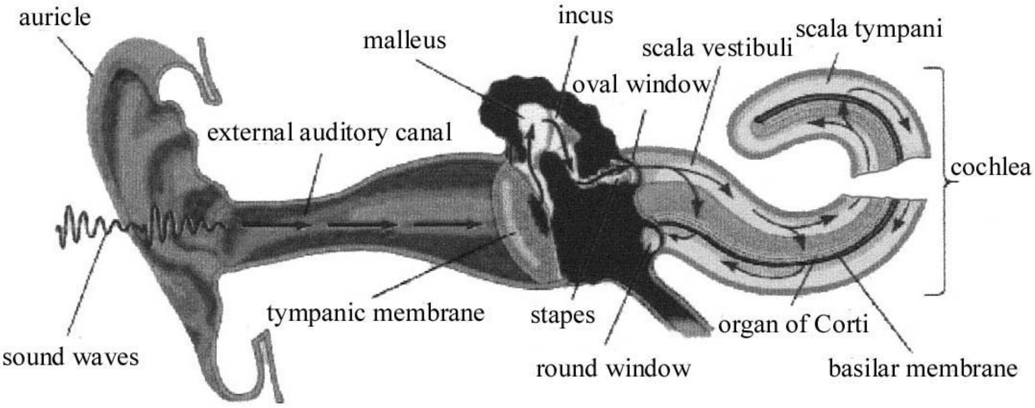

Figure 1. Demonstration of the mechanism of the hearing. The sound waves travel through the external auditory canal until they reach the tympanic membrane, causing the tympanic membrane and the attached chain of auditory ossicles to vibrate. The motion of the stapes against the oval window sets up waves in the fluids of the cochlea, causing the basilar membrane to vibrate. This stimulates the sensory cells of the organ of Corti to send nerve impulses to the brain.

The organ of Corti is a collection of cells, including the sensory hair cells that sit on the basilar membrane. Along the upper surface of organ of Corti, called the reticular lamina, hair bundles protrude from the tops of the hair cells. Each hair bundle is composed of two to four rows of hairlike structures called stereocilia. Nerve fibers from the auditory nerve are connected to the bottom of each hair cell. There are two types of hair cells in the cochlea, i.e. inner hair cells (IHCs) and outer hair cells. The IHCs are primarily connected to the auditory nerve by afferent fibers, which deliver neural signals to the brain. The OHCs, on the other hand, are connected primarily by efferent nerve fibers, which receive neural signals from the central auditory system. The human cochlea contains approximately 4000 IHCs and 12000 OHCs. They are typically distributed as one row of IHCs and three rows of OHCs along the basilar membrane. The tectorial membrane lies on the top of the organ of Corti and is attached to the tips from the stereocilia of OHCs, but is not directly in contact with the stereocilia of IHCs (Pickles, 1988; Gelfand, 1990), as illustrated in Figure 2.

Hair cells are primarily mechanoelectric transducers. Due to shearing movement between the tectorial membrane and the reticular lamina, the hair cells convert displacement of the hair bundle into a change in the receptor current flowing through the cells by gating of ion channels that are located near the top of the hair bundle, i.e. tip links of the stereocilia. OHCs act as electromechanic transducers as well by converting voltages across their cell membranes into their length/volume changes, i.e. the source of active cochlear mechanism (Flock et al., 1986; Hudspeth and Markin, 1994; Allen and Neely, 1992; Manley and Gallo, 1997).

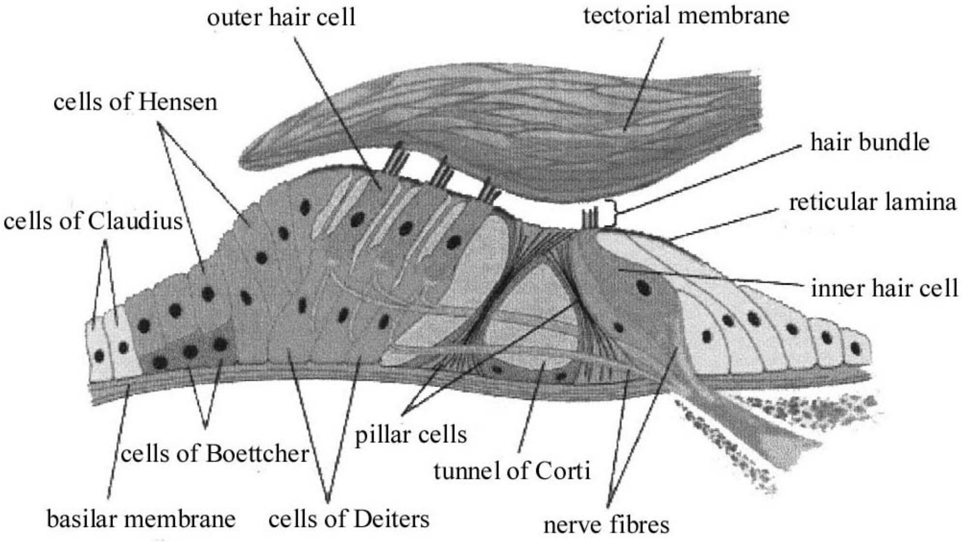

Figure 2. Structure of the organ of Corti. Nerve fibers from the auditory nerve are connected to the bottoms of OHCs by efferent fibers (primarily) plus afferent fibers and IHCs by afferent fibers (primarily). The tectorial membrane lies on the top of the organ of Corti and is attached to the tips from the stereocilia of OHCs, but is not directly in contact with the stereocilia of IHCs. Due to shearing movement between the tectorial membrane and the reticular lamina, the hair cells are stimulated by the bending of stereocilia.

Von Békésy (1951), by direct observation of the vibration pattern from the specimens of human cochlea, described that each point on the basilar membrane is mechanically tuned to a certain frequency known as characteristic frequency (CF). When the ear is stimulated by a pure tone the vibration on the basilar membrane grows in amplitude as the wave travels from the base towards the apex, which peaks at the CF, and dies out rapidly, i.e. the traveling wave. When the CF is high the basilar membrane vibration is located towards the base of the cochlea (Hubbard, 1993, Nobili et al., 1998; Ulfendahl, 1997). The range of CF for the normal human ears is about 20 to 20000 Hz.

Cochlear nonlinearity and active cochlear mechanism

Gold (1948) suggested that active mechanisms were required in order to achieve the sharp frequency selectivity on the basilar membrane. The finding of the otoacoustic emissions (OAEs) (Kemp, 1978) and the existence of actin (Flock et al., 1982) in the hair cell gave direct evidences to the existence of an active cochlear mechanism. Low auditory thresholds and the sharply tuned traveling wave on the basilar membrane are associated with normal auditory sensitivity and frequency selectivity. OAEs indicate that an active process is involved in the normal cochlear function. The outer hair cells are the source for this acoustic energy, which feed the energy back into the traveling wave in response to auditory stimulation. Part of the cochlear nonlinearity is a result of this active mechanism. Cochlear nonlinearity can also be a result of a passive process on the basilar membrane, which is broadly tuned. The cochlear nonlinearity can be shown as a nonlinear growth of cochlear responses with stimulus intensity and on the offset of the position of basilar membrane during stimulation. The cochlear nonlinearity is responsible for the generation of combination tones or distortion-product OAEs (DPOAEs).

The presence of combination tones was first demonstrated psychophysically by a cancellation method (Goldstein, 1967; Smoorenburg, 1972b) by introducing an extra external tone. Later, the combination tones were physiologically detected (Kim et al., 1980; Allen and Fahey, 1993). The two most important of these are the difference tone (quadratic distortion-product), f_2-f_1, and the cubic distortion-product, $2f_1$-f_2. Different combination tones are not generated by the same types of nonlinearities, e.g. generation of the cubic distortion-product $2f_1$-f_2 depends on symmetrical nonlinearities to the input whereas the difference tone f_2-f_1 relies on asymmetrical nonlinearities. Quadratic distortion can normally be detected at higher signal levels, and may be generated by an asymmetrical movement of basilar membrane in response to acoustic stimulation and therefore it may reflect the operating point on the basilar membrane (Frank and Kössl, 1996, 1997; Chang and Norton, 1997).

The cubic distortion-product, on the other hand, can be heard at lower signal levels (near auditory threshold at $2f_1$-f_2) (Goldstein, 1967; Smoorenburg, 1972a; Giguere et al., 1997). It is thought that the cubic distortion-product is generated by an active nonlinear mechanism in the cochlea. The volume and length changes of outer hair cells after the acoustic stimulation (Flock et al., 1986) give the active contribution from the outer hair cells to the movement of basilar membrane, and thus add energy into the system in a nonlinear manner. Therefore, the cochlear nonlinearity will generate the DPOAEs and the active cochlear nonlinearity is necessary for achieving normal auditory sensitivity and frequency selectivity. Modeling the generation of DPOAEs on the basilar membrane has been described by Mills

(1997), Strube (1986), and Talmadge et al. (1999).

The active cochlear nonlinearity can be estimated by multi-component DPOAEs (Kemp, 1997; Lind, 1999). The pattern of the multi-component DPOAEs indicates a great deal about the cochlear nonlinearity. The input-output function of the active cochlear nonlinearity can be calculated by using a generating model of the multi-component DPOAEs. Pickles (1988) and Hall (1974) described a polynomial power series model for two-tone stimuli. By analysis of the levels of multi-component DPOAEs the input-output function of the active cochlear nonlinearity can be calculated.

Cochlear nonlinearity can also be described as a compressive nonlinearity and this nonlinearity can be approximated by a hyperbolic function (Johnstone et al., 1986). If the auditory threshold (10 dB SPL) corresponds to 0.3 nm motion of the basilar membrane the nonlinearity shows half saturation at 10 nm. The compressive nonlinearity can produce multi-component DPOAEs as well. Actually the compressive hyperbolic nonlinearity can also be expressed as polynomial power series (Abramowitz and Stegun, 1964; Korn and Korn, 1961). However, the compressive hyperbolic model expressed as polynomial power series has different coefficients than those of the polynomial power series model. An interesting viewpoint is that the generating mechanism of multi-component DPOAEs may be level dependent, i.e. different generating models are valid at different stimulus levels. It should then be possible to calculate the input-output function directly from the levels of multi-component DPOAEs by using the polynomial power series model or the hyperbolic compressive nonlinear model.

Cochlear and retrocochlear lesions

Hearing loss arising from the cochlea or auditory nerve is known as sensorineural hearing loss (SNHL), which can be caused by noise (acoustic trauma), age (presbyacusis), tumor (e.g. acoustic neuroma), ototoxic drugs/substances, infections, or may be congenital. SNHL of cochlear origin can be a result from the damage of outer and/or inner hair cells and their neighbors, e.g. tip links of stereocilia, rootlets of stereocilia in the cuticular plate, fused stereocilia, tectorial membrane, and destruction of the hair cells. The most common SNHL is noise-induced hearing loss (NIHL). Human susceptibility to the noise is different for different individuals. Recent investigations show that this individual susceptibility of the hair cells might be predicted by measuring otoacoustic emissions (OAEs) (Hotz et al., 1993; Engdahl and Kemp, 1996).

The basilar membrane in the cochlea in responses to a sound is characterized by features of high sensitivity, sharp frequency tuning and nonlinearity (Giguere and Woodland, 1994a,b). However, physiologically, the damage of outer hair cells gives rise to a loss of sharply tuned tips of the tuning curves in the auditory nerve fiber responses, which is therefore directly associated with the loss of both auditory sensitivity and frequency resolution. The damage of inner hair cells mainly shows a reduced auditory threshold sensitivity (Pickles, 1988). Psychoacoustically, the loss of the sharply turned tip in the psychoacoustical tuning curves (PTC) for the sensorineural hearing loss makes loudness of a stimulus grow abnormally quick with the stimulus intensity, known as loudness recruitment (Moore, 1982). This phenomenon can be used as a tool for the diagnosis of the sensorineural hearing loss and thereafter for hearing rehabilitation of patients.

NIHL is an example of sensorineural hearing loss of cochlear origin. It involves the process from a temporary threshold shift (TTS) to a permanent threshold shift (PTS). Nordmann et al. (2000) showed that the damaging mechanism between TTS and PTS is different, i.e. TTS is a result of the uncoupling between the stereocilia of OHCs and tectorial membrane and PTS is associated with permanent hair cell damage. However, if we think about the fact that a TTS for 8-hour noise exposure can usually give similar threshold shifts as PTS of NIHL for 10-year noise exposure (same type of audiogram) (Passchier-Vermeer, 1974), there should be a relation between PTS and TTS. The relationship between TTS and PTS can be described by the equal energy principle as well; i.e. the degree of noise-induced hearing loss is directly related to the total acoustic exposure energy. The borderline between the temporary and the permanent threshold shifts, i.e. if the hearing loss is reversible, is still not well explained or defined for the cochlear process from the temporary to the permanent threshold shift (Borg et al., 1995). In animal experiments, it has been shown that the noise may damage both outer and inner hair cells. It has been proved that an outer hair cell damage leads to an elevation of the auditory threshold with unaltered or improved threshold of acoustic stapedius reflex. Inner hair cell damage on the other hand causes an elevation of the acoustic reflex threshold (Borg et al., 1995). This different effect of outer and inner hair cell damage correlates well to a different effect on the response curves of single auditory nerve fibers (Borg et al., 1990).

The protection against noise-induced hearing loss has been directed to manipulation of the cochlear metabolism and blood circulation, to activation of medial cochlear efferents, and to sound conditioning (Canlon and Dagli, 1996). Recent research showed that one of the reasons for the hearing loss is genetic deficiency of antioxidant enzyme, e.g. superoxide dismutase (SOD), in the cochlea. The ear can be protected against NIHL and hearing loss can reduced by modulating antioxidant enzyme in order to control for the level of free-oxygen radicals in the cochlea.

SNHL is directly related with some auditory diseases, e.g. Ménière´s disease (Horst and Kleine, 1999) and tinnitus (Janssen et al., 1998). Harris and Probst (1992) reported from 31 patients with Ménière´s disease that it was exceptional for an affected ear to have a TEOAE response when auditory thresholds were greater than 25 dB HL. Therefore, understanding of SNHL can be achieved by the measuring and analyzing OAEs, which should lead to a better diagnosis and treatment of different cochlear and retrocochlear disorders (Delb et al., 1999; Eddins et al., 1999; Engdahl, 1996; Engdahl et al., 1996; Hall and Lutman, 1999; Kværner et al., 1995; Marshall and Heller, 1998; Whitehead et al., 1992a,b; Vinck et al., 1999; Zurek and Clark, 1981, Prieve and Falter, 1995).

Otoacoustic emissions

Otoacoustic emissions (OAEs) measured in the external ear canal are normal by-products of the active process in hearing, which was discovered by Kemp (1978). Outer hair cells (OHCs) are thought to be the active source in the generation of this energy. The main technical requirement of measuring of OAEs is to reduce background noise and use an appropriate stimulation protocol in order to separate the low-level OAEs from undesired stimulus components and the artifacts. The lack of the solution for this requirement is probably the reason of why OAEs were not detected before Kemp (1978), even if the low-noise and high-sensitivity microphone were available long before 1978. OAEs are classified according to the type of acoustic stimulation to induce them. Spontaneous OAEs (SOAEs) are narrow-band and low-level signals, which are produced without acoustic stimulation and appear in about 25-70% of normal hearing ears (Kemp, 1979; Penner et al., 1993; Cheng, 1998a, Köhler et al., 1986; Martin et al., 1990b; Talmadge et al., 1993; Penner and Zhang, 1997). Transient evoked OAEs (TEOAEs) occur after brief stimuli, e.g. clicks (Kemp, 1978; Cheng, 1993). Distortion-product OAEs (DPOAEs) are produced by simultaneous stimulation with two primary tones at frequencies of f_1 and f_2 ($f_1<f_2$), and occur e.g. at the frequency $2f_1-f_2$, corresponding to a cubic distortion product (Brown and Kemp, 1984). Jaramillo et al. (1993) demonstrated the distortion products from a single outer hair cell. When the ear is stimulated by a constant tone, stimulus-frequency OAEs (SFOAEs) are presented as an additional acoustic energy from the cochlea, and a special recording procedure of two measurements at different stimulus levels is required to extract the SFOAEs by scaling the complex amplitudes and vector subtraction of responses (Kemp and Chum, 1980; Brass and Kemp, 1991). Multi-component DPOAEs or combination tones can be observed at frequencies corresponding to $mf_1-(m-1)f_2$ for odd order distortions, and to mf_2-mf_1 for even order distortions (m being integer numbers) (Moulin and Kemp, 1996a,b).

The characteristic of OAEs includes:

1. OAEs are a consequence of the active process in the inner ear and the motility of the OHCs is the source. Therefore OAEs can be used to identify frequency ranges of normal hearing in the pathological ears (Kemp et al., 1990a).

2. The generation of OAEs is highly nonlinear, leading to the use of nonlinear protocol for recording of TEOAEs and to the generation of DPOAEs.

3. TEOAEs are delayed responses with respect to the onset of acoustic stimulation. Therefore TEOAEs can be used to extract place associated information on the basilar membrane, e.g. the information on traveling wave and the synchronization of SOAEs on TEOAEs, leading to the use of time-frequency analysis of TEOAEs and the approaches on optimization of the TEOAE recording windows (Whitehead et al., 1995; Tognola et al., 1999a; Uppenkamp and Kollmeier, 1994). These can make the TEOAE based hearing screening methods more effective and reliable.

4. The generation of OAEs can be influenced by other factors as well; e.g. OAEs can be synchronized and phase locked with some physiological and neuro activities (Long and Talmadge, 1997; Smurzynski and Probst, 1998; Mom et al., 1999), OAEs may show a frequency shift and/or level suppression e.g. via the cochlear efferent system (Micheyl et al., 1999; Zheng et al., 1997; Micheyl and Collet 1994; Talmadge et al., 1998; Scholz et al. 1999a,b; Schloth, 1983; Rabinowitz and Widin, 1984; Neumann et al., 1997; Lutman and Deeks, 1999; Murphy et al., 1995a,b, 1996; Zizz and Glattke, 1988).

5. The measuring of OAEs is non-invasive and highly reproducible and therefore especially suited for neonatal hearing screening (Hunter et al., 1994; Kei et al., 1997; Lutman et al., 1997).

6. The recording of OAEs relies on a healthy middle ear (Wada et al., 1995; Magnan et al., 1997).

Both TEOAEs and DPOAEs can be used to identify hearing loss due to outer hair cell dysfunction in the frequency range where they would be normally expected. In various studies TEOAEs were never found when the hearing loss at the best frequency was worse than 40 dB HL (Collet et al., 1993a,b; Tognola et al., 1999b). Furthermore, when pure-tone threshold averages (PTA; 1000, 2000 and 4000 Hz) were greater than 40 dB HL, TEOAEs were never observed in response to 86 dB p.e.SPL clicks (Norton, 1993). In ears with sloping hearing losses (Johnsen et al., 1993) the thresholds at 1 kHz and 2 kHz were most important for the presence of

TEOAEs. Generally speaking, DPOAEs are more sensitive and frequency specific than TEOAEs. However the measurement of TEOAEs seems more effective than the measuring of DPOAEs. Therefore, the measuring of TEOAEs is a good method for hearing screening (Brass and Kemp, 1994a,b) and the measuring of DPOAEs is a good method for detail research on cochlear disorders. Some technical methods have been proposed to further increase the reliability and efficiency of the OAE measurement e.g. artificial neural network (Buller and Lutman, 1998), maximum length sequence (MLS) method (Thornton, 1993; Rasmussen et al., 1998), TEOAE descriptors (Hatzopoloulos et al., 1995), nonlinear system identification (Chertoff et al., 1996; Krishnan and Chertoff, 1999), dual response audiometry (TEOAEs and ABR) (Hoth and Lochmann, 1999), TEOAEs through bone-conduct stimulation (Purcell et al., 1998), TEOAEs with an open recording system (Withnell et al., 1998), electrically evoked OAEs (Nutall and Ren, 1995), DPOAE latency (O Mahoney and Kemp, 1995; Whitehead et al., 1996b), and multiple tone pairs DPOAEs (Kim et al., 1997).

In the detection of early cochlear damage from noise, the changes in OAEs seem to be more sensitive than the changes in pure-tone thresholds (Hotz et al., 1993). This gives a possibility to study the individual noise susceptibility, the cochlear mechanism for the transition from a temporary threshold shift to permanent threshold shift, and the possible strategies for hearing protection based on the protection of active process of the outer hair cells.

OAEs can be influenced by the medial cochlear efferent system (Harrison and Burns, 1993; Hood et al., 1996; Zwicker, 1983). Contralateral stimulation and selected blockers of the efferent system allow exploring the efferent activity via the crossed olivo-cochlear bundle (COCB). The hearing process is contralaterally innervated by the efferent system, as well as ipsilaterally, It is believed that the efferent system is influenced by the negative feedback loop via the efferent fibers, which regulates hair cells and provides hair cell protection from the damages (Rujol, 1994). OAEs can also provide information on the auditory fine structure (Sun et al., 1994a,b; Kapadia and Lutman 1999). On the other hand, OAEs can influence performance of psychoacoustical tasks (Smurzynski and Probst, 1999). Different types of OAEs are related (Zwicker and Schloth, 1984; Kulawiec and Orlando, 1995; Moulin et al., 1993; Osterhammel et al., 1996). Yates and Withnell (1999) reported that TEOAEs are responses of intermodulation distortion-products. OAE level will be reduced during and after aspirin consumption (Long and Tubis, 1988) and quinine administration (McFadden and Pasanen, 1994; Berninger et al., 1998).

Figure 3 shows some key points on the measuring and the signal processing techniques used in the present investigations. In general, a sensitive, low-noise microphone and receiver(s) (for evoked OAEs) are needed and placed in the sealed external ear canal. While measuring, the specially designed stimulus and recording protocols are applied.

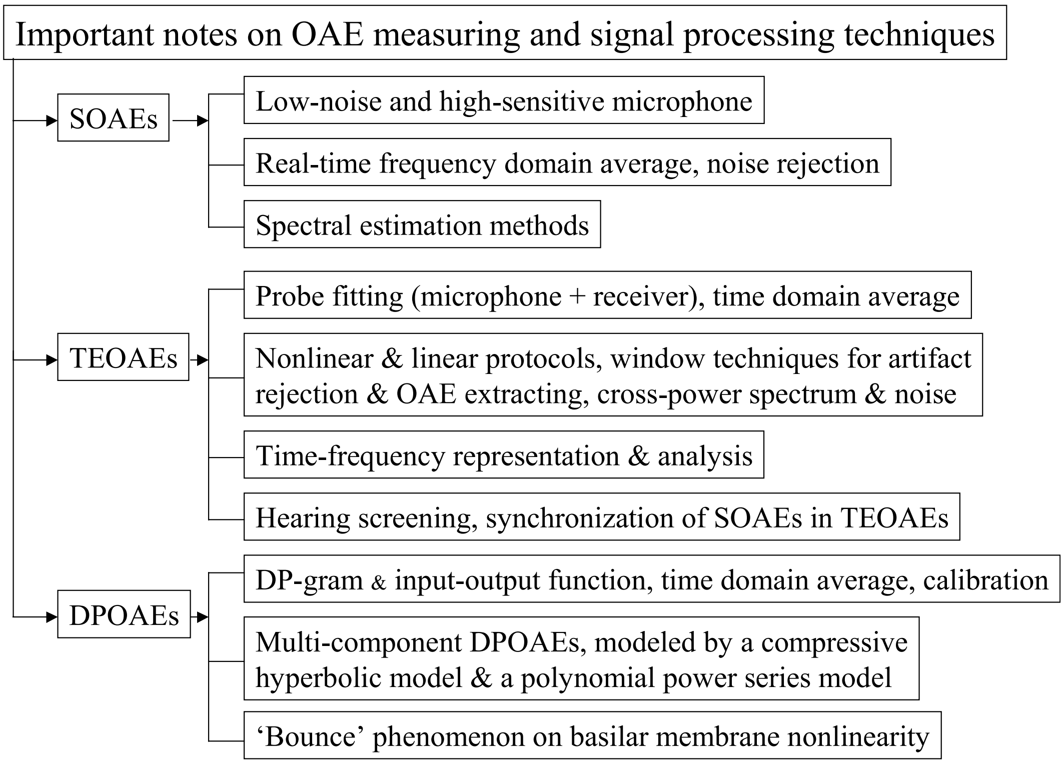

Figure 3. Important notes on measuring and signal processing techniques for different types of OAEs applied in the present investigations.

Time-frequency analysis

A typical goal in signal processing is to find a representation in which certain attributes of a signal are made explicit. In principle, there is an infinite number of ways of describing the given signal. A signal's time and frequency representations are the two most useful representation methods. However, we traditionally have studied signals either as a function of time or as a function of frequency, in spite of the fact that the majority of signals in the real world, e.g. OAEs, have time-dependent spectra. It is more useful to characterize the signal in time and frequency domains simultaneously i.e. by time-frequency representation (TFR) (Hlawatsch and Boudreaux-Bartels, 1992; Pitton et al., 1996; Sessarego et al., 1989; Smits, 1992). By using TFR we can consequently better understand the underlying mechanism of how OAEs were generated. In general, OAEs are usually concentrated on the TFR, whereas the random noise tends to spread on the TFR and the stimulus artifact is usually distributed in the fixed region on the TFR. Therefore, TFR is also a powerful tool for removing noise and artifact from the signal. Consequently, the signal-to-noise ratio (SNR) can be improved in the TFR of TEOAEs.

Theoretically, TFRs are classified into linear and bilinear (quadratic) representations. The linear TFRs include e.g. short-time Fourier transform (STFT) and wavelet transform (WT) (Hess-Nielsen and Wickerhauser, 1996; Wit et al., 1994; Tognola et al., 1997). The fundamental idea behind the linear transformations is to compare the signal with predesigned elementary functions. Then the different elementary functions lead to a variety of different TFRs. For example, the elementary function for STFT is sinusoid signals and the elementary function for the WT is time-scaled wavelets.

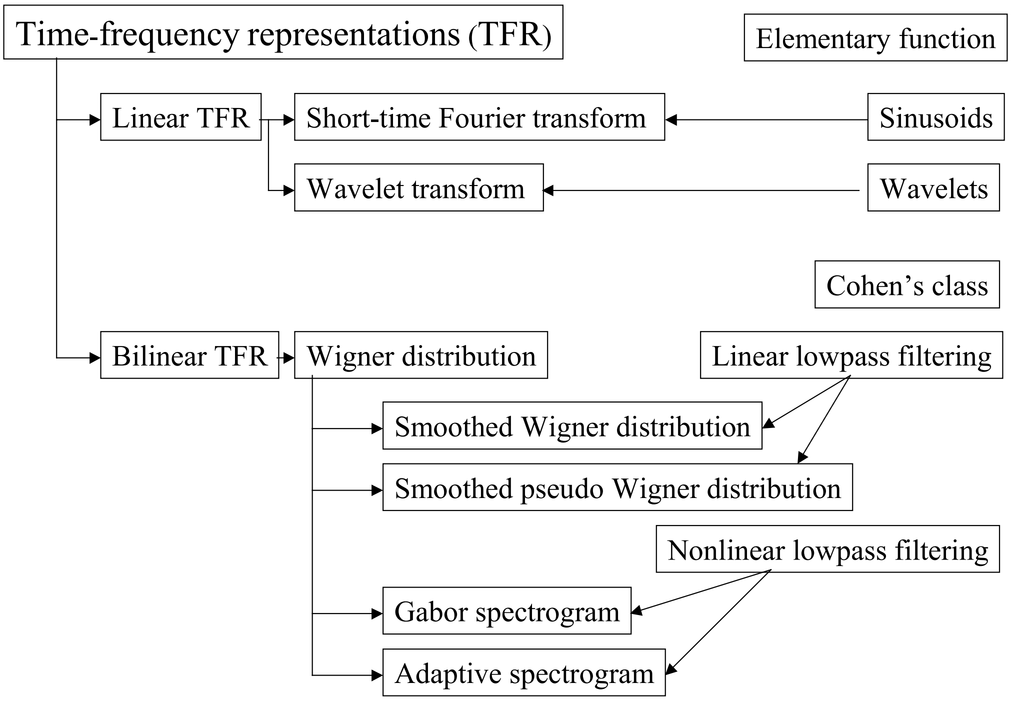

Figure 4. A schematic demonstration of linear and bilinear (quadratic) time-frequency representations.

Therefore, the linear TFRs are usually applied in the analysis of the signals generated from a stationary process. For non-stationary signals, such as speech signal and OAEs, the frequency contents of the signals change as a function of time. The classical Fourier analysis is not adequate for these signals. Therefore, the quadratic TFRs, e.g. Wigner distribution (Wigner-Ville spectrum) (WD), are introduced (Wigner, 1932), which can better characterize the signal's time-dependent spectra. The main deficiency of the Wigner distribution is the cross-term interference. However, it has long been recognized that the cross-terms always occur in the middle of the time-frequency components and are highly oscillating. By linear lowpass filtering (convolution in the other domain) characterized as Cohen's class, a smoothed Wigner distribution can be reached (Krattenthaler and Hlawatsch, 1993; Bekir, 1993). A nonlinear lowpass filtering described as time-frequency distribution series can be used as well, which lead to the Gabor spectrogram. Once the decomposition process in the Gabor spectrogram is adaptively and repeatedly performed in order to match different elementary functions, the adaptive spectrogram has been achieved (Qian and Chen, 1996). The smoothed pseudo Wigner distribution (SPWD) is an improved version of the smoothed Wigner distribution (Claasen and Mecklenbräuker, 1980). In the SPWD, two independent smoothing functions for both the time and the frequency domains are used in order to optimally reduce the cross-term interferences. Figure 4 is a schematic demonstration of time-frequency resolution of linear and bilinear (quadratic) time-frequency representations applied in the present investigations.

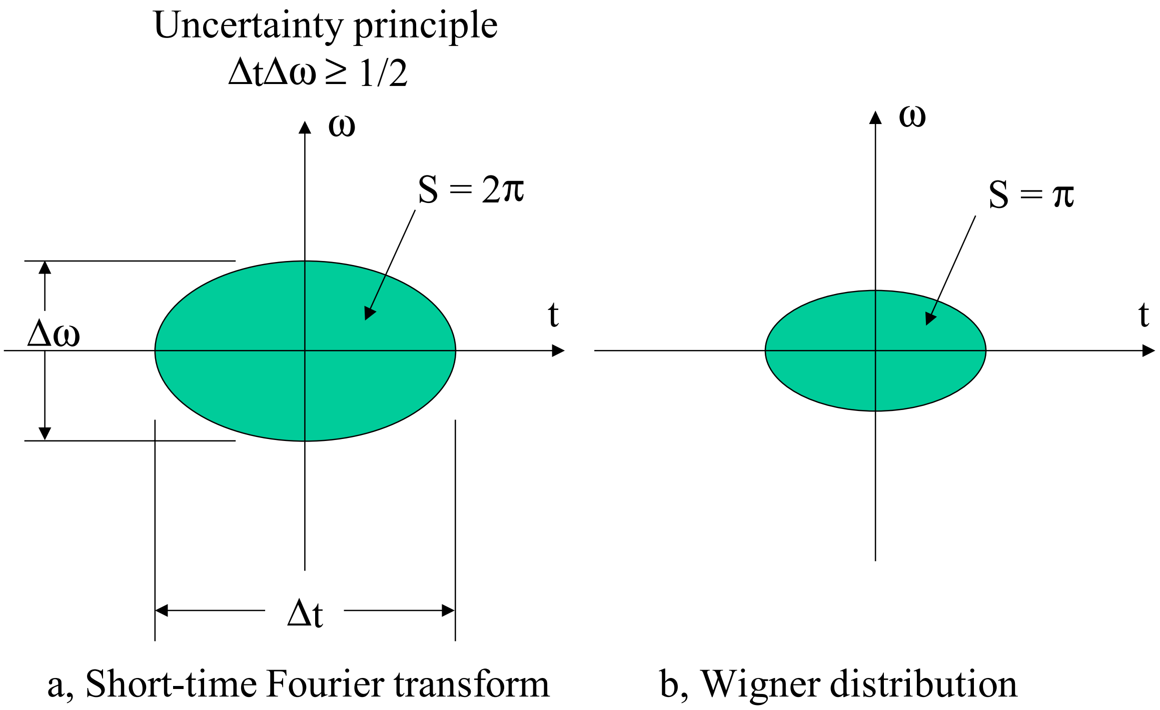

Figure 5. The uncertainty principle and minimum time-frequency resolution by (a) short-time Fourier transform (STFT) and (b) by Wigner distribution (WT). Proof was given by Qian and Chen (1996).

Generally, the time and the frequency resolutions are related in the TFRs, and a good time resolution requires a short analysis window, which will give a bad frequency resolution and vice versa. The minimum time-frequency resolutions in the linear TFRs are limited by the uncertainty principle, i.e. $\Delta_t \Delta_\omega \geq 1/2$ (proof given by Qian and Chen, 1996), where Δ_t and Δ_ω are the time and frequency bandwidths, respectively. The minimum time-frequency area is 2π for the Gaussian function concentrated at (0,0) in the time-frequency plane as demonstrated in Figure 5a. For the quadratic TFR, the equivalent minimum time-frequency resolution in the Wigner distribution calculated by the minimum time-frequency area is π (Qian and Chen, 1996) as illustrated in Figure 5b. Therefore, the SPWD can have a better time-frequency resolution than STFT. The cross-term interferences can be reduced in SPWD as well, and the reduction of the cross-term can be controlled by the time and the frequency smoothing windows independently.

The Wigner distribution has some other good properties:

1. Time marginal condition; i.e. the integral of WD along ω at the instant time equals the signal's instant energy multiplied by 2π.

2. Frequency marginal condition; i.e. the integral of WD along t for a frequency equals the signal's power spectrum density at that frequency.

3. The total energy of the original signal equals the energy contained in the Wigner distribution in the time-frequency plane (Qian and Chen 1996).

These properties are very important, especially for the analysis and quantifying of TEOAEs.

TEOAEs consist of a large number of individual components that overlap in both time and frequency domains. The analysis of shape and localization of TEOAE pattern can give information on the TEOAE origin and on the activity of outer hair cells along the basilar membrane as a function of time.

Since TEOAEs can be measured objectively and non-invasively, measuring of TEOAEs and analysis of TEOAEs with the time-frequency method will play an important role in the hearing screening routine, especially for neonatal screening.

Spectral estimation

The general task of the spectral estimation is to extract the signal's frequency characteristics from the noise and the disturbance (Carter and Nuttall, 1983). Usually, the spectral estimation is based on procedures directly employing the fast Fourier transform (FFT). The spectral analysis using this approach makes the method computationally efficient and produces reasonable good results. However, there are several inherent performance limitations of the direct FFT approach. The first is that the frequency resolution, i.e. the ability to distinguish two closely located frequency components, is limited by the duration of recording. The second is that unavoidable natural data windowing makes the energy in the signal lobe leak into the sidelobes in the frequency domain. This leaked energy will mask or distort lower level signals that may be located in the same frequency band. The sidelobes can be reduced by careful selection of the data window at the expense of reduced frequency resolution.

The generating mechanism of the signal could be a stochastic process, and the recording time is always limited. Thus, the spectral estimation of the signal is in fact based on the signal's statistics. Then, the estimation quality can be evaluated by the estimation error, described by the variance, and the estimation bias, between the real signal's frequency characteristics and it's spectral estimation. The methods for performing spectral estimation can be classified into two main classes: the classical approaches (non-parameter methods) and modern approaches (parameter methods). In the classical methods, the spectral estimation by directly using FFT on the raw data is referred to as the periodogram, and the spectral estimation based on indirect approach via the signal's autocorrelation function known as Blackman and Tukey method (BT method) (Nuttall and Carter, 1982). In the modern method or parameter method, the spectral estimation is based on the modeling of the process, estimating the parameters of the model e.g. by using raw data and, then, performing the spectral estimation by using the parameters of the model. The major advantage in the modeling approach is a higher frequency resolution. The performance of the spectral estimation is then dependent on how well the assumed model matches the process under analysis, which may be reasonably assumed by the knowledge about the process from which data samples are taken. The parameter method of spectral estimation can also avoid the power leakage problem associated with the data windowing in the classical spectral estimation methods.

The spectral estimation will usually give the result as a function of the frequency, e.g. power spectrum or power spectrum density of the signal. The power spectrum and power spectrum density are closely related. In the power spectrum, e.g. periodogram, a peak on the periodogram represents the power of the signal at that frequency. For the power spectrum density, the area under the function of the power spectrum density is equal to the power of the signal. They are related in such a way that $P_s = P_{sd}\,\Delta f$ (Kay and Marple, 1981), where P_S represents periodogram, P_{sd} is power spectrum density and Δf represents the frequency resolution of the spectral estimation. In the practical situation, e.g. in our OAE applications, the OAEs are acoustic energy and measured in the ear canal as a sound pressure level using a microphone. Therefore, it is usually calibrated to dB SPL by using 20 µPa as a reference. Then, either the power spectrum or the power spectral density will give an identical result of the spectral estimation after acoustic calibration.

SOAEs are narrow-band signals buried in higher-level acoustical noise of various origins (Probst et al., 1991). The cochlear generating mechanism of SOAEs involves a highly tuned filter process, which corresponds to an all-pole process of an autoregressive (AR) model. Therefore, an AR model was selected in the modern approach. An infinitely high-order AR model is approximately equivalent to an autoregressive-moving average (ARMA) model or a moving average (MA) model (Kay and Marple, 1981) with limited order, and vice versa. This is important since even if the AR model is not a good approximation of the cochlear generating mechanism of SOAEs a good spectral estimation can still be achieved by increasing the order of the AR model. Furthermore there is a computationally more efficient algorithm in the estimation of the parameters in the AR model than in the ARMA or the MA model (Kay and Marple, 1981). Therefore the high-order AR model was applied.

When a high-order AR model is applied to estimate the spectrum of SOAEs, a minimum prediction error power can be calculated as a function of the model order. For the spectral estimation of SOAEs, the minimum prediction error power will usually be monotonously decreased as the model order is increased. The minimum prediction error power (one of parameters in the AR model, see paper V) will always occur at a higher model order.

Since the ARMA model can be seen as extended from the AR model, we can say that the generating mechanism of SOAEs is an ARMA process as well. However, if we think about the facts that SOAEs are narrow-band signals, the generation of SOAEs involves highly tuned filter processes, the source of SOAEs is related with the distribution of OHCs on the basilar membrane, and an AR model is inherently suitable to express a narrow-band process (Kay and Marple, 1981), it might be concluded that a high-order all-pole process is involved in the generation of SOAEs.

Accurate assessment of the spectral characteristics of the SOAE signals is needed for providing direct clues as to how the cochlea works. In the present investigation of spectral estimation of SOAEs, an average periodogram, a reduced variance estimate i.e. pseudo Blackman-Tukey (PBT) spectrum (Keilson et al., 1993; Khanna et al., 1993), and a model based high-order AR estimate were applied as demonstrated in Figure 6. The performances of the different estimates were compared as well. Spectral estimation of SOAEs depends on the methods used. The performance of different spectral estimation methods may also depend on the SNR of the SOAE signal and the measuring system. When a high-order AR model was applied to estimate SOAEs, the analysis of minimum prediction error power revealed that a high-order all-pole process is involved in the generation of SOAEs, rather than a purely harmonic process.

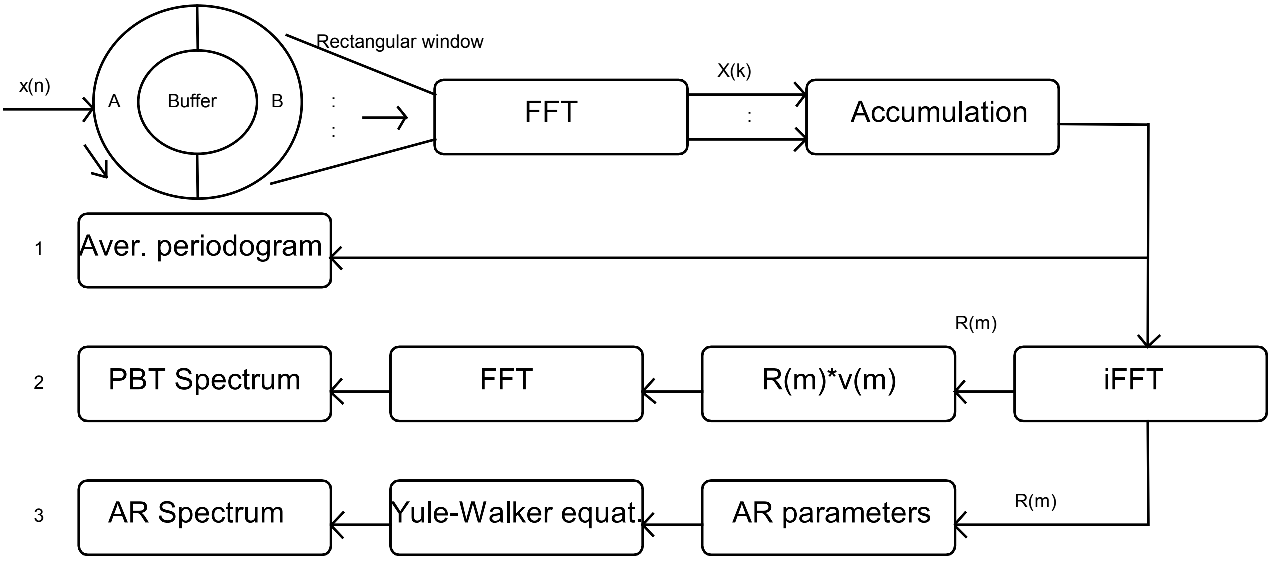

Figure 6. Illustrative demonstration of the spectral estimation of SOAEs.

Auditory susceptibility to low frequency tone exposure and the "bounce" phenomenon

After exposure to a loud, but not traumatic tone at a low frequency, the auditory pure-tone threshold will recover in a non-monotonic way, which is improved with a maximum at about 1 minute immediately after the exposure (better pure-tone threshold), then it reaches to an overshot minimum at about 2-3 minutes, known as 'two minute bounce' (Hirsh and Ward, 1952), there after towards the normal. The 'bounce' phenomenon on DPOAEs was investigated by Kirk and Patuzzi (1997) and Kirk et al. (1997), and they showed that 'bounce' is caused by a small shift of basilar membrane operating point and/or a disruption of the salt balance within the cochlea during the low-frequency tone exposure. Kemp (1986) observed a post-exposure increase in the level of TEOAEs at about 1 minute after the low-frequency tone exposure and suggested that there is a transient hypersensitivity in the cochlea immediately after the low-frequency tone exposure, which is caused by changes of the active process in the cochlea.

At mid-lower stimulus levels, multi-component DPOAEs are generated by an active mechanism of the basilar membrane nonlinearity and the input-output function of the basilar membrane nonlinearity can be calculated using the levels of the multi-component DPOAEs. The active basilar membrane nonlinearity for generating multi-component DPOAEs can be modeled by a polynomial power series model at mid-lower stimulus levels. The degree of basilar membrane nonlinearity for generating specific multi-component DPOAEs can be quantified as $1-\rho_{xy}^2$, where ρ_{xy} is a correlation coefficient derived from the input-output function of the basilar membrane nonlinearity. The analysis of the 'bounce' recovery pattern of the active basilar membrane nonlinearity from individuals may give objective information on an individual ability to recover from a temporal threshold shift (TTS).

AIMS OF THE STUDY

The general aim of this study has been to develop measuring methods in order to be able to study the cochlear condition and localization of cochlear lesions by measuring otoacoustic emissions (OAEs) with enhanced signal processing techniques. In order to achieve this goal, several signal processing methods have been applied to the recording and the estimation of OAEs in the presence of noise and artifacts, as well as improving the means of representing the extracted information from OAE recordings. Focus has been placed on the refinements of the signal processing methods and the measurement tools created can be used to investigate the function of the inner ear, especially the function of outer hair cells (OHCs).

More specifically, the aims have been focused on:

1. A time-frequency method for signal representation and analysis of transient evoked otoacoustic emissions (TEOAEs) via smoothed pseudo Wigner distribution.
2. To devise an optimal recording protocol based on time-frequency analysis of TEOAEs for neonatal hearing screening. To apply the time-frequency analysis of TEOAEs for studying sensorineural hearing loss (SNHL).
3. To study the relationships among TEOAEs, spontaneous OAEs (SOAEs) and distortion-product OAEs (DPOAEs), as well as the relationship to physiological factors and the stimulus parameters.
4. To study and apply signal processing methods for spectral estimations of SOAEs.
5. To determine the benefits of signal processing methods for estimation of active cochlear nonlinearity by multi-component DPOAEs and by introducing the generating models of DPOAEs.
6. To develop a method to study the "bounce" phenomenon in relation to basilar membrane nonlinearity.

MATERIAL AND METHODS

Subjects

In paper I, 54 normal-hearing neonatal ears were measured. In paper II, 397 ears from neonatal hearing-screening programs from three different countries have been used. In paper III, 40 normal-hearing ears and 40 ears with sensorineural hearing loss of adult subjects have been studied. In paper IV, 32 normal-hearing ears were tested. In paper V, 32 normal-hearing ears were involved. Some more normal hearing and hearing impaired ears were also involved in the studies. Table 1 shows an overview of the main tested ears in the present investigation.

Equipment

In paper I, TEOAEs were measured by a TAMP3 system (developed by our department) with a digital signal processing system (DSP) consisting of a TMS32010 signal processor, 12 bit AD/DA converters, tracking anti-aliasing filters, program controllable attenuator and preamplifier. B-type probes (Otodynamics Ltd) were used. The DSP system was controlled by an IBM compatible personal computer (PC). TEOAE acquisition programs have been written for both TAMP and PC, and the SPWD program runs under PC's environment.

In paper II and paper III, ILO-92 equipments (software version 4.20 and 5.6H) were used, and both the linear and nonlinear stimulus protocols were applied.

In paper IV, paper V, paper VI and paper VII, a hardware system (System II, Tucker-Davis Technologies) consisting of an array processor card (AP) with DSP32C signal processor, 16 bit AD/DA converters, anti-aliasing filters, program controllable attenuators, and an OAE probe system (ER-10C, Etymotic Research) were used. They were controlled by an IBM compatible PC. Software programs for recording and analysis of SOAEs, TEOAEs and DPOAEs were developed.

System calibration

Different calibration procedures were applied for the recording of the different types of OAEs. Stimulus and recorded levels were calibrated to sound-pressure level in dB SPL (using 20 µPa as a reference) or peak-equivalent sound-pressure level in dB, p.e.SPL, at the eardrum position on an ear simulator (Brüel & Kjær type 4157, according to IEC 711) with a measurement amplifier (Brüel & Kjær type 2607).

Statistical methods and computer simulations

Statistical methods such as paired *t* test, Fisher's exact test, multiple regression, one-way or two-way analysis of variance (ANOVA) and correlation analysis were used in the present investigations. Statistical analyses were performed with the computer programs of SOLO (version 4.0, BMDP Statistical Software) for a general statistics and STATGRAPHICS (version 5.0, Statistical Graphics Corporation) for the statistics and graphic representations.

In paper II and paper III, a non-parametric statistical method was used because the samples were not normally distributed. The statistical analyses were performed with Wilcoxon test for paired data, Mann-Whitney U test for group data and Spearman's rho test for correlation analysis, using a confidence interval of 95% as significant level. The statistical program SPSS (version 6.1, SPSS Science Software) was used in the studies.

Computer simulations were performed with the computer programs of MATLAB (version 5.1, MathWorks Inc.) and LabVIEW (version 4.0, National Instruments) in the present investigations.

Table 1. An overview of the main part of the tested ears in the present investigation.

	Paper I	Paper II	Paper III	Paper IV	Paper V
N =	54	397	80	32	32

RESULTS

Time-frequency representation and analysis of TEOAEs

Time-frequency analysis of TEOAEs via SPWD (paper I, paper IV)

TEOAEs can be transformed into the time-frequency plane by SPWD to give a three-dimensional pattern. The analysis of the shape and localization of TEOAE pattern and the comparison of the pattern difference will give information on the cochlear condition and the TEOAE origin. SPWD is an effective method to separate the TEOAEs from artifacts and noise as well. The time-frequency analysis of TEOAEs demonstrated that SOAEs can be synchronized with the stimuli in TEOAE responses and that the commonly recorded TEOAEs are a mixed complex of synchronized SOAEs and TEOAEs (see Figure 6 in paper I and Figure 2 in paper IV). The synchronized SOAEs on TEOAEs can be identified as horizontal bars in the TFR of TEOAEs.

An averaged SPWD of the TEOAEs from 54 normal neonatal ears was presented. From this averaged SPWD of TEOAEs we can conclude that the various frequency components demonstrate different times of arrival. By comparison with the SPWD of an individual neonatal ear it is possible to comment on the cochlear conditions of a neonate. The method has the potential to be used in neonatal hearing screening program.

Optimization of the TEOAE recordings for neonatal screening using TFR (paper II)

By time-frequency analysis of time-frequency distributions of an average linear and nonlinear TFR of TEOAEs from 50 neonatal ears, it has been demonstrated that there are no statistically significant differences between the linear and nonlinear TFRs with a time window of 4.0 – 19.5 ms in any frequency band for stimulus levels of 68 dB p.e.SPL (linear protocol) and 82 dB p.e. SPL (nonlinear protocol – the fourth click in every group of four clicks has reversed polarity and the level is increased by a factor of 3) respectively. In order to further increase the SNR of the linear TEOAEs a 10 ms time window of 4.0 – 14.0 ms was proposed and applied in 397 neonatal ears. The results show an optimal linear protocol for neonatal screening. Using 4.0 - 14.0 ms time window will give a better SNR and a lower noise level of TEOAEs than a corresponding nonlinear TEOAE protocol for the higher frequency bands (2 kHz and up). The time-frequency method was proposed as a part in the AHEAD project (Advancement of Hearing Assessment Methods and Device) by the Laboratory of Otoacoustic Emission of University of Ferrara in Italy. The method was applied at three neonatal clinics in Europe (Hatzopoulos et al., 2000).

Optimization of the TEOAE recording protocols by using TFR for normal hearing subjects and SNHL cases (paper III)

By using time-frequency (TF) analysis for the linear and nonlinear recordings of TEOAEs from normal hearing subjects, it can be shown that a 4.0 - 14.0 ms window will contain a 87 % and 88.5% of the total TF energy for the linear and nonlinear protocols respectively. Therefore, using a 10 ms TEOAE response segment instead of the 20 ms TEOAE response, the most important spectral information of TEOAEs from the cochlea will still be maintained.

Significant improvements in SNR were observed after shortening the TEOAE response window from 20 to 10 ms for the linear as well as for the nonlinear protocols. The linear recording protocol provides a better SNR of TEOAEs and a higher correlation estimate from the standard correlation output of the ILO-92 instrument.

Time-frequency analysis of TEOAEs from SNHL cases indicated that the TF energy was significantly reduced in the mid to high frequency bands, however, this reduction did not correlate well with the elevation of the audiometric thresholds.

Different types of OAEs, their interrelations and relations to other factors

Spontaneous otoacoustic emissions (SOAEs) (paper IV, paper V)

SOAEs were present in both ears in 56% of the normal-hearing subjects, and absent in both ears in 31% of subjects (N = 32). There were a few cases with monaural SOAEs at lower levels. The total rate of presence of SOAEs was 63% (female: 93% and male: 39%). SOAEs in both ears were generally symmetric, but detailed features e.g. the frequencies of SOAEs and the number of SOAEs in both ears were different. The amplitude of SOAEs ranged between -11 and 18 dB SPL and the frequency range was 0.35 to 8 kHz, with the majority between 1 to 4 kHz. SOAEs can be a single or multiple (most cases). The multiple SOAEs can interact and produce distortion-products as reported by Burns et al. (1984) and Norrix and Glattke (1996).

Transient evoked otoacoustic emissions (TEOAEs) (paper I, paper IV)

TEOAEs were present in all observed normal-hearing ears (N = 32) for 85 dB p.e.SPL stimuli (mean±SD in dB SPL: 12.7±3.5 for left ears and 14.1±4.2 for right ears). TEOAEs in both ears were symmetric in general, but the detailed features were different. The input-output function, the response level of TEOAEs as a function of stimulus level, was calculated. Synchronized SOAEs were observed in some of the TEOAE recordings, especially at lower stimulus levels.

Distortion-product otoacoustic emissions (DPOAEs) (paper IV)

DPOAEs were measured in all observed normal-hearing ears (N = 32). The input-output function, the DP level as a function of stimulus level at certain frequencies, and the DP-gram, the DP level as a function of stimulus frequencies at a certain stimulus level, were calculated.

Lonsbury-Martin and Martin (1990) reported that the input-output function of DPOAEs for normal ears had a monotonic slope or a non-monotonic slope with a notch between low and high stimulus levels. The slope varied from 0.8 to 0.95. The DP-gram of DPOAEs for normal ears showed a two-peak shape between 1 to 8 kHz, with a dip between the peaks at about 3 kHz, and the curve fluctuated beyond ±10 dB. In the present investigation, the input-output function of DPOAEs confirms this observation. However, the special calibration procedure (see paper IV) applied in this study gives a rather flat DP-gram, which fluctuates about ±3 dB between 1 to 8 kHz. The calibration for the DPOAE measurement is an important issue as described by Siegel (1994), Siegel and Hirohata (1994), Siegel (1995), Whitehead et al. (1996a) and Chertoff and Chen (1996).

SOAEs and subject factors (paper IV)

SOAE results showed a tendency of female and right ear advantages for normal-hearing subjects (N = 32). The main difference between male and female results is the amount of high frequency emissions. The right ear advantage of SOAEs exists also at high frequencies. Fisher's exact test was used to test the significances of the gender and the ear effects to the variability of presence/absence of SOAEs for the left as well as the right ears. The gender effect was statistically significant for the left ears ($p<0.05$) and for the right ears ($p<0.03$). The tendency of the ear effect to the presence/absence of SOAEs was not statistically significant.

TEOAEs vs. SOAEs and subject factors (paper IV)

TEOAE response levels were analyzed as a function of the presence/absence of SOAEs and subject factors. Two-way ANOVA was applied to test the gender effect and the presence/absence of SOAEs to the variability of TEOAEs for the left as well as the right ears separately for normal-hearing subjects (N = 32). The gender effect contributing to the variability of the TEOAEs were statistically significant ($p<0.01$ for left ears; $p<0.05$ for right ears). The tendency of the presence/absence of SOAEs and pure-tone threshold average for all tested frequencies contributing to the variability of the TEOAEs were not significant for the left or the right ears separately. The tendency of the right ear advantage of TEOAEs was not statistically significant.

DPOAE vs. SOAEs, TEOAEs and subject factors (paper IV)

DPOAEs were analyzed as a function of the presence/absence of SOAEs, the response level of TEOAEs and subject factors. Two-way ANOVA was applied to test the gender effect and the presence/absence of SOAEs to the variability of DPOAEs for the left as well as the right ears separately for normal-hearing subjects (N = 32). The gender effect contributing to the variability of the DPOAEs for the right ears were statistically significant ($p<0.05$). Correlation analysis was performed between DPOAEs and TEOAEs. The correlations for the left ears ($r=0.46$, $p<0.05$) and for the right ears ($r=0.68$, $p<0.01$) were found to be statistically significant.

Spectral estimation of SOAEs

Evaluation of three methods for spectral estimation of SOAEs (paper IV, paper V)

The average periodogram produces a reasonably good result for the spectral estimation of SOAEs. In theory the frequency resolution of the average periodogram is limited by the recording duration. In our measuring program of SOAEs, the measuring parameters are sampling frequency Fs = 25 kHz, frame size = 4096 samples, and averaging over 32 frames, which give a frequency resolution of 6 Hz and a recording duration of 5.24 seconds. The energy leaks into the sidelobes. This effect is associated with the data windowing and will make the estimated spectrum broader than the true spectrum. In the pseudo Blackman-Tukey (PBT) spectrum, the spectrum is smoothed to delimit the random peaks associated with FFT algorithm in the spectral estimation of the broadband signal. The variance of the PBT spectral estimation is reduced to achieve a smoothed spectrum at the expense of a reduced frequency resolution. The benefit from the reduced variance estimate and the cost of the frequency resolution are related with the choice of the time-domain window. A Bartlett window was applied, which has been proved to give the best result. In the high-order AR spectrum, two sinusoids separated by 6 Hz are possible to identify, therefore the frequency resolution is increased. The frequency smoothing is unnecessary since the AR spectrum is smoothed. The 3 dB bandwidth is reduced compared with the average periodogram since the estimate extends the data out of the window by using a forward and a backward linear prediction, which makes the estimation of an AR spectrum more close to the true spectrum of the signal.

The detailed comparison among the average periodogram, the PBT spectrum, and AR spectrum shows that the AR spectrum has the best performance on frequency resolution. It demonstrated the narrowest 3 dB bandwidth, and it gives a rather good estimate for the broadband noise spectrum as well. The average periodogram produces a reasonably good estimation for the SOAEs with the best algorithm efficiency, but gives the worst estimation for the broadband noise spectrum. PBT estimate has a smoothed spectrum with the worst frequency resolution, which can be used to identify true SOAEs from noise peaks associated with the inherently bigger variance for the FFT algorithm in the average periodogram. Spectral estimation of SOAEs indicated that 3 dB bandwidths are different for different estimates and that the bandwidths of SOAEs are not related with the frequency.

SOAE AR modeling and minimum prediction error power (paper V)

When a high-order AR model is applied to estimate the spectrum of SOAEs, the minimum prediction error power can be calculated as a function of the model order. The minimum prediction error power will usually be monotonously decreased as the model order is increased while estimating SOAEs. The minimum prediction error power calculated as a parameter in the AR model will always occur at the higher model order. Therefore a high-order all-pole process is involved in the generating of SOAEs, which is not purely a harmonic process.

Different methods to discriminate SOAEs from the noise (paper V)

At higher SNR, the high-order AR spectrum demonstrated the highest frequency resolution. At lower SNR, compared to the average periodogram, the high-order AR spectrum showed an almost equivalent frequency resolution in the estimation of the SOAE spectrum, and showed a better performance in the estimation of the noise spectrum. The average periodogram had a reasonably good performance with the best algorithm efficiency. The reduced variance estimate of SOAEs gave a smoothed spectrum, which could be used to identify true SOAEs from the noise peaks.

Multi-component DPOAEs and active cochlear nonlinearity

Compressive hyperbolic cochlear nonlinearity (paper VI)

The compressive nonlinear model for generation of distortion-products was simulated at a location on the basilar membrane. The hypothesises are that the transmission gains/dampings in both directions between the probe (in the ear canal) and a location on the basilar membrane are linear, and that the generating mechanism of multi-component DPOAEs at the location on the basilar membrane is nonlinear. The system output from a linear system is proportional to the system input. Therefore, in the frequency domain of a linear system, the system output is a shifted version of the input in dB scale. By comparison of computer simulation of the input-output function of the compressive hyperbolic nonlinearity with the input-output function of DPOAE measurements from subjects in the dB vs.

dB scale, it has been demonstrated that the compressive hyperbolic nonlinearity generates bigger distortion-products at the higher signal level and much smaller distortion-products at the lower signal level compared with the "real-ear" cubic DPOAE measurement. For the higher signal level, Johnstone et al. (1986) also noticed the difference between a compressive saturating mechanism and a combined nonlinearity, and between the saturating mechanism and the observations. Therefore at the higher signal level (> 80 dB SPL) the cochlea does not act as a limiter to protect the ear, but turns to be more linear, which will, on the other hand, generate less distortion-products.

Level dependence of cochlear nonlinear mechanism (paper VI)

The cubic DPOAEs can be heard at lower signal levels (near auditory threshold at $2f_1$-f_2) (Goldstein, 1967; Smoorenburg, 1972a). When the primary level goes down the compressive hyperbolic model will produce much less cubic distortion-products than the cubic DPOAEs measured on the ears. Therefore, another level dependent multi-component DPOAE generating mechanism is hypothesized. Actually, at the lower signal level, the polynomial power series model for the generation of distortion-products is more natural, because the polynomial power series model can generate stronger multi-component distortion-products even at the lower levels.

The nonlinearity from the polynomial power series model (paper VI, paper VII)

For the polynomial power series model, the nonlinear contribution of the input-output function at the samples' maximum distribution peak for stimulation of two tones can be calculated. The results show that the nonlinear contributions of the input-output functions at different stimulus levels are rather level dependent, and the nonlinear contribution has a relatively high level even at the lower stimulus levels (see paper VI for details).

Basilar membrane nonlinearity and the "bounce" phenomenon

Quantifying basilar membrane nonlinearity (paper VI, paper VII)

The active basilar membrane nonlinearity for generating multi-component DPOAEs can be modeled by a polynomial power series model at mid-lower stimulus levels. The input-output function of the basilar membrane nonlinearity can be calculated using the levels of the multi-component DPOAEs. The degree of basilar membrane nonlinearity for generating specific multi-component DPOAEs can be quantified as $1-\rho_{xy}^2$, where ρ_{xy} is a correlation coefficient derived from the input-output function of the basilar membrane nonlinearity. The basilar membrane nonlinearity is distributed from 0.0 (totally linear) to 1.0 (totally nonlinear).

The effect of low-frequency tone exposure on the basilar membrane nonlinearity and the "bounce" phenomenon (paper VII)

After the ears were exposed to a loud, but not traumatic tone at lower frequency, an approach has been tried to investigate the 'bounce' phenomenon on the active cochlear nonlinearity. The analysis of the 'bounce' recovery pattern of the active basilar membrane nonlinearity from individuals can give information on an individual's ability to recover from a temporal threshold shift (TTS) objectively.

An example of the 'bounce' phenomenon on the basilar membrane nonlinearity after a low-frequency tone exposure is shown in Figure 7. The nonlinearity at -1 minute post-exposure time indicates the basilar membrane nonlinearity before the low-frequency tone exposure and the nonlinearity from 20 seconds to 5.0 minutes post-exposure time indicates the basilar membrane nonlinearity after the low-frequency tone exposure. The low-frequency exposure tone had a frequency of 500 Hz, a level of 90 dB SPL, and a duration of 60 seconds.

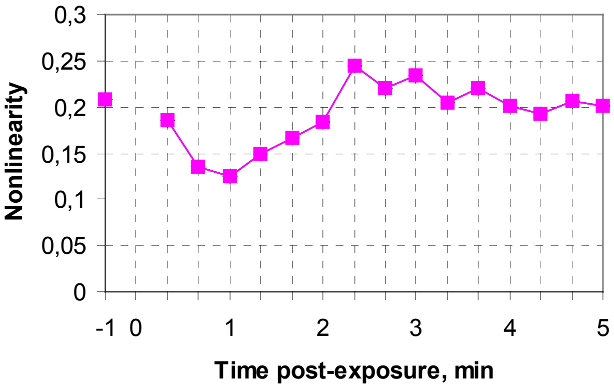

Figure 7. An example of the 'bounce' phenomenon after a low-frequency tone exposure for an ear from a normal-hearing subject.

DISCUSSION

Issues on time-frequency representation and analysis of TEOAEs

Short-time FFT and SPWD (paper I, paper IV)

In the short-time Fourier transform based spectral analysis method i.e. spectrogram, it is assumed that the signal is stationary within a specific analysis window. When the spectral content changes rapidly over time, like for TEOAEs, an accurate estimate is impossible. Using SPWD is an effective way to meet this problem.

Implementation of linear protocol for neonatal screening (paper II)

Since TEOAEs can be measured objectively and non-invasively, they are potentially powerful for screening purposes, especially for neonates and young children (Bray and Kemp, 1987).

For the optimization of the TEOAE recording protocol in the neonatal screening a linear protocol with 10 ms time window (4.0-14.0 ms) has shown several advantages. First, it provides the TEOAE recordings with a lower noise and a higher SNR in the 2.0, 3.0 and 4.0 TEOAE frequency bands. Secondly, the increase of the SNR can result in a decrement in the numbers of the TEOAE sweeps required, which is advantageous in a clinical use of the method, where the TEOAE acquisition time is of great importance.

The analysis of the TEOAEs with the linear protocol and a shorter 10 ms time window for different laboratories demonstrated that the proposed protocol could be implemented without systematic differences caused by different measuring environments or differences among neonatal populations.

TFR of TEOAEs for normal hearing as well as SNHL subjects (paper III)

For normal hearing ears, a cumulative energy distribution of TFR of TEOAEs using a shorter TEOAE segment, 4-14 ms, gave a better SNR and lower noise level than the processing of the whole 20 ms TEOAE response. However, TEOAEs with shorter segment also demonstrates a lower response level.

For SNHL group, the hearing threshold elevation is not well correlated with the TEOAE response level. The SNHL group were sub-classified into "low SNHL" (TEOAE response levels were 2.2-10.6 dB SPL) and "high SNHL" (TEOAE response level were above 10.6 SPL). The SNHL patients with the same threshold elevation can be classified into different SNHL sub-group depending on the level of the TEOAE responses. Other factors in the sound propagation chain, e.g. middle ear properties, may also play a role.

For the high and low-SNHL classes, the majority (90%) of the TF energy is concentrated in a relatively small TEOAE segment, i.e. 4.4 - 13.2 ms and 4.6 - 10.8 ms respectively. Therefore, the TF contours of the high SNHL class presented a long energy-dispersion pattern. The low SNHL class presented a shorter energy dispersion pattern and only at the low to mid frequencies (1- 2 kHz).

The comparison between normal subjects and SNHL cases suggests that the TEOAE responses from the normal subjects are characterized by a broader bandwidth, the differences between normal and high-SNHL cases are enhanced in the mid to high TEOAE frequency bands, and there are statistical differences between the low and high-SNHL classes across all TF bands.

OAEs, their interrelations and relations to other factors

OAEs and audiometric thresholds (paper I, paper IV)

There are relations between audiograms and TEOAEs (Kemp et al., 1990a,b), and the TEOAEs can be used to identify frequency ranges of normal hearing in pathological ears. In various studies TEOAEs were never found when the hearing loss at the best frequency was worse than 40 dB HL (Collet et al., 1993a,b). Furthermore, when pure-tone averages (PTA; 1, 2, and 4 kHz) were greater than 40 dB HL, TEOAEs were never observed in response to 86 dB SPL clicks (Norton, 1993). In ears with sloping hearing losses (Johnsen et al., 1993) the thresholds at 1 and 2 kHz were most important for the presence of TEOAEs. Time-frequency signal representation and analysis have a better SNR than one-dimensional signal analysis (Qian and Chen, 1996), therefore the critical threshold to get SPWD of TEOAEs should reach or exceed 40 dB HL for hearing impaired ears.

For the group of normal hearing subjects, there were tendencies showing that SOAEs were negatively correlated with the pure-tone threshold for higher frequencies, and TEOAEs were negatively correlated with the pure-tone averaged thresholds for all frequencies. This might be explained by: (1) the cochlear activity at higher frequency region on the basilar membrane in the cochlea will contribute both to the SOAE generation and to the hearing sensitivity of higher frequencies, and (2) TEOAEs are related with the hearing sensitivity from low to high frequencies.

Synchronized SOAEs on TEOAEs influencing the input-output function of TEOAEs (paper I, paper IV)

Wable and Collet (1994) mentioned that SOAE peaks show up in about 90% of the TEOAE recordings, and that this proportion was reduced at the higher stimulus levels. Kulawiec and Orlando (1995) suggested that SOAEs added to the overall response level of TEOAEs. Wit et al. (1981) first demonstrated the synchronization of SOAEs in TEOAEs in human subjects. Synchronized SOAEs can be phase-locked with the stimuli in the TEOAE recordings, especially at lower stimulus levels (Cheng, 1993). The reason may be that the synchronized SOAEs need the right amount of energy to phase-lock with the stimulus. Therefore the synchronized SOAEs are limited at higher stimulus levels, are phase-locked with the TEOAE response at mid levels, and will be gradually separated from the phase-locking when stimulus level is further lowered. The total response, i.e. synchronized SOAEs plus TEOAEs, will be increased compared to the response without SOAEs. Therefore, the commonly recorded TEOAEs are a mixed complex of synchronized SOAEs and TEOAEs. The measured results of TEOAEs in either the time or the frequency domain, e.g. response level, will be strongly influenced by the synchronized SOAEs. The time-frequency analysis of TEOAEs by wavelet analysis (Wit et al., 1994) or by smoothed pseudo Wigner distribution (Cheng, 1993) is a solution for this problem. Synchronized SOAEs can be identified as horizontal bars in the time-frequency plane, which are distinguished from the frequency sweeping in the TEOAEs. Therefore the 'real TEOAE' response and response levels excluding contributions from the synchronized SOAEs can be better estimated by directly reading from the TEOAE pattern in the time-frequency representation.

Gender effect on the input-output function of TEOAEs and DPOAEs (paper IV)

As indicated by Probst et al. (1991) and Morlet et al., (1995), the gender related OHC arrangements, e.g. OHC size and distribution in the inner ear, and the higher noise exposure risk for male population make the female advantage of OAEs. The input-output function of TEOAEs for the female subjects shows about 4 dB higher level than for the male subjects at all stimulus levels ($p<0.01$). The presence of SOAEs in the female subjects was more frequent than that of male subjects. Therefore the presence of SOAEs and the input-output function of TEOAEs show a similar gender effect.

The gender effect in the input-output function of TEOAEs is rarely described in the literature. However, TEOAEs are closely related with SOAEs (Kemp, 1986; Wable and Collet, 1994) and SOAEs have been found to be related with gender (Probst et al., 1991). Therefore it can be concluded that gender effect plays an important role in the input-output function of TEOAEs. However, secondary factors may also play roles, e.g. gender related differences in the middle ear transfer function and in the volume of the external ear canal, which are at least different in the anatomic size between the two sexes (Probst et al., 1991).

DPOAEs for female subjects are stronger than in the male subjects. The dip in the input-output function of DPOAEs has the same tendency as the dip in the input-output function of TEOAEs, but the dip is located at an input SPL of 55 dB. This is because the stimulus level definition in TEOAE and DPOAE measurements is different, e.g. stimulus levels are defined as dB SPL in the DPOAE measurements and as dB p.e.SPL in TEOAE measurements. Lonsbury-Martin et al. (1990a,b) and Martin et al. (1990a) reported that lower DPOAE "threshold" by about 10 dB at 4 kHz for females than for males ($p<0.01$) occurred in the absence of differences in hearing thresholds. In addition there was a tendency for females to exhibit larger DPOAEs in response to 75 dB SPL primary stimuli at 4 kHz. The present study also revealed that the biggest difference in DPOAE responses between females and males is at 4 kHz of stimulus GM frequency, 75 dB SPL stimulus level.

Issues on spectral estimation of SOAEs

The bandwidth and the closest frequency interval of SOAEs (paper V)

The AR spectrum shows that the 3 dB bandwidth of SOAEs is less than 10 Hz and that this bandwidth is not frequency dependent. Inner ear physiology demonstrates that the frequency distribution of a single outer hair cell or one column of outer hair cells is between 5-8 Hz (Pickles, 1988; Gelfand, 1990), which meets the bandwidth estimation of SOAEs by AR spectrum, i.e. 8.15±4.79 Hz (paper V). Therefore the SOAEs should be generated by a single outer hair cell or one column of outer hair cells. The bandwidth of SOAEs can also be approximately estimated by the average periodogram. However the influence of the energy leakage function of the rectangular window must be considered. This gives about the same estimated bandwidth of SOAEs as the AR spectrum.

Physiologically, OHCs have the ability to synchronize external signals at their characteristic frequencies demonstrated by the cochlear microphonic (CM) (Pickles, 1988), and this phenomenon will be highly tuned at CFs by the OHC active mechanism. When SOAEs are generated by a single outer hair cell or one column of outer hair cells they will be sustained by cochlear resonance and synchronously locked to their CFs. Therefore the estimated frequency and bandwidth of SOAEs can be directly related to the cochlear partition on which they are generated and mapped to the OHC's CFs.

In the present investigation, the closest SOAEs were 34 Hz apart, shown by both the average periodogram and the high-order AR spectrum. In this case, it seems that the SOAEs have different sources, i.e. they are two different SOAEs.

Estimation of SOAEs at lower SNR (paper V)

The main problem in the AR spectrum is that the spectral estimation is sensitive to the noise level (Kay and Marple, 1981). At lower SNR the frequency resolution is no longer better than that of the periodogram. In fact, for the signal with lower SNR, the modeling of an AR process for the generation of SOAEs is no longer valid, since it is an ARMA process. Although this can be approximated by a high-order AR model, it is still restricted by the fact that the spectral estimation of an AR model can follow the true spectrum better at spectral peaks than at the valley. However the noise mentioned here is mainly broadband electronic noise which comes from the microphone and the measuring system, which will be reduced with further technique development. At lower SNR, the frequency averaging frames for the average periodogram can be increased beyond 30 suggested by Probst et al. (1991) for further reduction of the estimation error variance.

Since the ARMA model can be seen as extended from the AR model, we can say that the generating mechanism of SOAEs is an ARMA process as well. However, if we think about the facts that SOAEs are narrow-band signals, that the generating of SOAEs involves highly tuned filter process (Burns et al., 1998; Talmadge et al., 1991; Van Dijk et al., 1996; Van Dijk and Wit, 1998), and that the source of SOAEs is related with physical distribution of OHCs on basilar membrane, we probably can conclude that a high-order all-pole process is involved in the generating of SOAEs, which is not purely a harmonic process.

Optimized way in the spectral estimation of SOAEs by different methods (paper IV, paper V)

The average periodogram is computationally efficient and produce a reasonably good result, which can be implemented for a real-time measuring of SOAEs. The reduced variance estimate can be used to discriminate true SOAEs from noise peaks that are associated with an inherently bigger variance in the periodogram. It can be applied in pseudo real-time combined with the average periodogram. These two spectral estimates can directly give information on SOAEs, e.g. presence/absence of SOAEs and levels of SOAEs, and have advantage of 'real-time'. Therefore they can be applied when the measurement of the subject is going on. The high-order AR spectrum has higher frequency resolution and higher sensitivity to periodical signals, and can be separately applied in the situation of e.g. the closely located frequency peaks, and in the estimation of the bandwidths of SOAEs.

Fluctuation and jittering of SOAEs (paper V)

Short-term fluctuations of SOAEs can appear as amplitude and/or frequency fluctuations. The measuring technique of SOAEs involves a frequency averaging in order to increase SNR. This average process is not sensitive to the short-term amplitude/frequency fluctuations of SOAEs at all. Therefore, when a SOAE fluctuates in amplitude the spectral estimation of SOAE will give a mean amplitude at SOAE frequency. When a SOAE fluctuates in frequency the spectral estimation of SOAE will depend on how SOAE is fluctuating. Time-frequency analysis (Cheng, 1993, 1998b; Wit et al., 1994; Tognola et al., 1997) of SOAEs can give some information on how these short-term SOAEs are fluctuating. In Figure 8, the upper trace shows the time domain SOAE signal in the ear canal of the left ear of a three year old child. The main panel demonstrates a time-frequency representation of SOAEs without using frequency average. The frequency jittering can be seen at about (14, 6.2), (12, 9), (14, 9)… (sec, kHz). The mechanism for this frequency jittering is unclear. It seems that there is a switch process behind this frequency jittering mechanism. The suppression effect via cochlear efferent system might be the source for this frequency jittering, and the detailed mechanism for this phenomenon needs to be further explored.

Quantifying basilar membrane nonlinearity and the noise effect on it

Compressive hyperbolic model expressed as polynomial power series (paper VI, paper VII)

The cochlear nonlinearity modeled by a compressive hyperbolic model and a polynomial power series model will demonstrate different input-output functions, even if they are calculated from the same multi-component DPOAEs. The compressive hyperbolic nonlinearity can also be expressed as polynomial power series (Abramowitz, 1964; Korn and Korn, 1961).

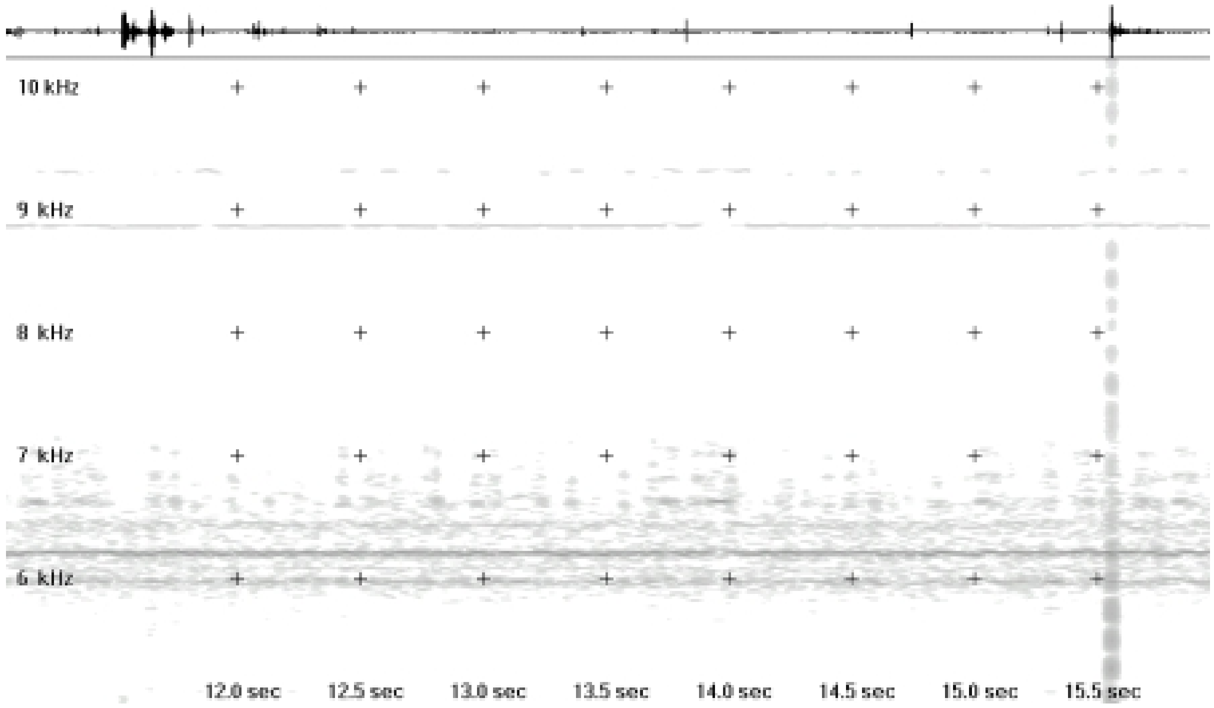

Figure 8. Real-time (no spectral average) time-frequency representation of SOAEs. The frequency jittering can be seen at about (14, 6.2), (12, 9), (14, 9)... (sec, kHz). The upper trace shows the time domain SOAEs in the ear canal.

However, the compressive hyperbolic model expressed as polynomial power series has different coefficients than the polynomial power series model. The compressive hyperbolic model expressed as polynomial power series has a compressed input-output function, even if it is expressed as a polynomial power series.

Linear vs. nonlinear system; passive vs. active system (paper VI)

A system is said to be linear if it satisfies the properties of homogeneity and superposition. For a homogeneous system, if an input x(t) results in an output y(t), then an input cx(t), where c is constant, will result in an output cy(t). The superposition means that if an input x1(t) results in an output y1(t) and an input x2(t) results in an output y2(t), then an input x(t)+x2(t) will result in an output y1(t)+y2(t). Therefore, the system output is proportional to the system input for the linear system, and the linear system will not produce distortion-products for a single or multiple inputs. A nonlinear system can be either passive or active. The active cochlear nonlinearity is a result of the active contribution from the outer hair cells to the traveling wave on the basilar membrane, which will add energy into the movement of basilar membrane for achieving normal auditory sensitivity and frequency selectivity at lower stimulus level. It should be noticed that the active process might exist parallel to a passive process for the cochlear nonlinear mechanism. A linear process will not generate distortion-products. Therefore, the multi-component DPOAEs are generated by the cochlear nonlinear mechanism. The generation of even order distortion-products caused by the asymmetrical movement of the basilar membrane to the input reflects the operating point on the basilar membrane, and the generation of odd order distortion-products demonstrates symmetrical nonlinear components to the input.

Compressive hyperbolic model and the Boltzmann function (paper VI, paper VII)

The generating mechanism of basilar membrane nonlinearity for mid-higher stimulus levels can be modelled by the compressive hyperbolic tangent function (Johnstone, 1986), which is actually equivalent to the Boltzmann function. Hudspeth and Markin (1994) showed the probability of an ion channel of the outer hair cell being open:

$$p_0 = \frac{1}{1+e^{-Z(X-X_0)/kT}}$$

where Z is gating sensitivity, X is the hair bundle's deflection distance from its resting position X_0, which is proportional to the displacement of the basilar membrane, and k is the Boltzmann constant and T is the absolute temperature. Let $X_0 = 0$, $Y = 2P_0-1$ and $a = Z/2kT$ then,

$$Y = 2p_0 - 1 = \frac{2}{1+e^{-2aX}} - 1 = \frac{1-e^{-2aX}}{1+e^{-2aX}} =$$

$$= \frac{e^{aX} - e^{-aX}}{e^{aX} + e^{-aX}} = \tanh(aX)$$

Therefore, compressive hyperbolic model and the Boltzmann function are equivalent by a linear transformation.

Three stages on the basilar membrane input-output function (paper VI)

Withnell and Yates (1998) suggested that the mechanical-to-electrical transduction on basilar membrane can be separated by three stages, i.e. a low-level region, a mid-level region and a high-level region, which separate the input-output function into effectively non-compressive linear, compressive nonlinear and ineffectively linear regions. They recognized the level dependent generating mechanism of cubic distortion-products as the present investigation. The present investigation showed that an active cochlear nonlinear mechanism dominates the generation of the multi-component DPOAEs at the lower level. An active cochlear nonlinear mechanism is necessary at the lower stimulus level in order to achieve a normal auditory sensitivity and frequency selectivity, e.g. as discussed by Probst et al. (1991).

Noise susceptibility at cell level (paper VI, paper VII)

Recent research (Flock et al., 1999) on an in vitro preparation of the temporal bone reported that the outer region of the organ of Corti, including outer hair cells and the third Deiters' cell with its attached Hensen's cells, exhibited dynamic structural changes, moving in toward the center of the cochlear turn during and after high-intensity sound exposure, and they take an active part in protection against noise trauma. The cochlear electrical response of cochlear microphonic confirmed structural observations. One interesting finding in their investigation is that the noise susceptibility for individual cochleas is quite different. The protection-recovery pattern can be tens of minutes, a couple of hours, or no change at all after a few exposures within hours but a strong response appears suddenly (Flock et al., 1999, figure 7, figure 11 and figure 12 respectively). Therefore, the way for an individual cochlea to protect itself against noise trauma may differ, and this difference will contribute to the individual noise susceptibility. Regarding the present investigation, the basilar membrane nonlinearity and the "bounce" phenomenon have a rather big difference for individuals as well (see paper VII). Is there any unknown mechanism under this individual difference? This is still remaining for further investigations.

Auto-regulation on basilar membrane nonlinearity (VII)

An auto-regulation has been noticed in measuring of the basilar membrane nonlinearity. The absolute level of the basilar membrane nonlinearity is fluctuated as a function of time in the time order of hours as a result of the physiological regulations. For an ear with normal hearing, the auto-regulation makes the basilar membrane nonlinearity in the morning higher (more nonlinear) than a couple of hours later. The fluctuation of OAEs has been reported in the literature. For example, Brienesse et al. (1998) showed long-term and short-term variations of SOAEs in the amplitude and the frequency for infants.

CONCLUSIONS

Signal processing methods have been applied in the recording and the estimation of OAEs in the presence of background noise and stimulus artifacts, and in the representation and extraction of OAE information. Focus has been placed on the refinements of the signal processing methods and the measurement tools created can be used to investigate the function of the inner ear, especially the outer hair cells. This thesis can be concluded as follows:

- TEOAEs can be processed by the smoothed pseudo Wigner distribution, and TEOAE patterns can be shown in the time-frequency plane. The characteristics of TEOAEs and cochlear condition can be estimated by inspection of SPWD patterns of the TEOAEs. This distribution pattern could map the functional activity along the basilar membrane.

- An optimal recording protocol based on time-frequency analysis of TEOAEs for neonatal hearing screening is proposed. A statistical analysis indicated that a linear TEOAE protocol windowed according to 4.0 - 14.0 ms generates a better SNR and a lower noise than the corresponding nonlinear TEOAE protocol.
- The time-frequency analysis of TEOAEs for normal and sensorineural hearing loss (SNHL) cases indicated that the TEOAE response could be faithfully represented by a 4-14 ms windowed version. A correlation analysis has indicated a weak, but not significant relationship between the TF energy at various frequency bands and the audiometric thresholds for the SNHL cases.
- Different types of OAEs are related and they may reflect the status of outer hair cells and cochlear condition from different perspectives. The contribution from the synchronized SOAEs to TEOAEs was demonstrated. The female and right ear advantages on OAEs were observed. Gender and the hearing thresholds are related with the presence/absence of SOAEs, and the response levels of TEOAEs and DPOAEs.
- Three spectral estimation methods for spontaneous OAEs (SOAEs) were investigated, namely an average periodogram, a reduced variance estimate and a high-order autoregressive (AR) estimate. The high-order AR spectrum showed higher frequency resolution than the other two estimates. The average periodogram gave a reasonably good spectral estimate of SOAEs with the best algorithm efficiency. The reduced variance estimate of SOAEs demonstrated a smoothed spectrum and can be used to discriminate the true SOAEs from the artifacts. When a SOAE is fluctuating the time-frequency analysis of SOAEs is proposed. When the high-order AR model was applied to estimate SOAEs, the analysis of minimum prediction error power revealed that a high-order all-pole process is involved in the generating of SOAEs, which is not a purely harmonic process. The spectral analysis of SOAEs suggested that the bandwidth of SOAEs is less than 10 Hz and not frequency dependent.
- Signal processing methods for estimation of active cochlear nonlinearity by multi-component DPOAEs have been proposed by introducing two models for the generation of DPOAEs, namely a polynomial power series model and a compressive hyperbolic model. Then the input-output function of the cochlear nonlinearity can be calculated from the multi-component DPOAEs. This input-output function represents the cochlear nonlinearity and will give the same pattern of multi-component DPOAEs as recorded from subjects. The results suggest that the generating mechanism of the multi-component DPOAEs is level dependent in such a way that, at lower stimulus levels, an active cochlear nonlinearity modeled by polynomial power series dominates the generation of the multi-component DPOAEs, at middle stimulus level the compressive hyperbolic model plays role for the cochlear nonlinearity, and at the higher stimulus level a linear process is involved.
- The degree of basilar membrane nonlinearity for generating specific multi-component DPOAEs can be quantified as $1-\rho_{xy}^2$, where ρ_{xy} is a correlation coefficient derived from the input-output function of the basilar membrane nonlinearity. The analysis of the 'bounce' recovery pattern of the active basilar membrane nonlinearity from an individual may give information on individual ability to recover from a temporal threshold shift (TTS) objectively.

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