Interaural Time Differences in Fine Structure and Envelope in Bilateral Electrical and Acoustical Hearing

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ARI

CIAP 2005

Conference on Implantable Auditory Prostheses

Asilomar Conference Grounds Pacific Grove, California

INTRODUCTION

Localization of sound sources is partly based on interaural time differences (ITDs). For lower frequencies, neural stimulation is synchronized to the phase of the carrier signal. Interaural difference of the phase, so called fine structure ITD (ITD FS), is important for determining the lateral position of the sound source. Current bilateral cochlear implant (CI) systems are running independently at the two ears. Most clinically applied coding strategies are based on amplitude modulation of electrical pulse trains. Thus, the ITD information is encoded in the temporal envelope (ITD ENV) only. Due to the independence of the systems, an interaural phase difference occurs in the pulse trains, which can be regarded as a ITD FS. Furthermore, a small interaural difference in the stimulation pulse rate leads to an uncontrolled, periodical change of ITD FS. If CI listeners are sensitive to the ITD FS cue, this could cause uncontrolled lateralization percepts.

This raises two questions:

- Is it necessary, and if, under which conditions, to interaurally synchronize the fine structure, ensuring ITD FS = 0? Since, in this case, the total ITD information can be received by the ITD in the envelope only, we call it the ENV condition.
- Can we obtain an improvement in lateralization discrimination (LD) by synchronizing ITD FS to the ITD information in the envelope? This type of synchronization corresponds to delaying the whole wave form – referred to as the condition waveform delay (WD).

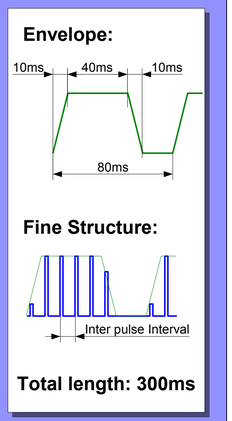
METHODS

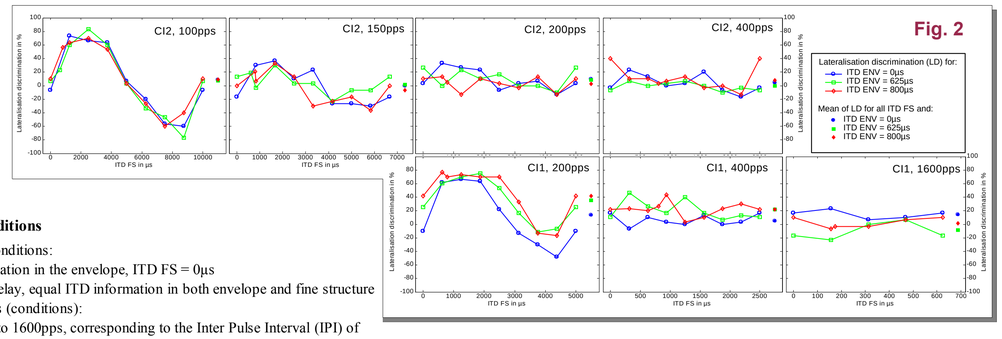
1. Subjects

- Four post-lingually deafened patients wearing *Med-El* CI-systems (see Tab. 1)
- Four normal hearing (NH) subjects listening to a simulation of CI stimulation

2. Stimuli (see illustration on the left border)

- Fine Structure: biphasic pulse trains with phase duration of 26.6µs/40µs (C40+/C40)
- Envelope: 4 Trapezoids with fast rising and falling edges and gaps inbetween
- Total length of the stimulus: 300ms





3. Experimental Conditions

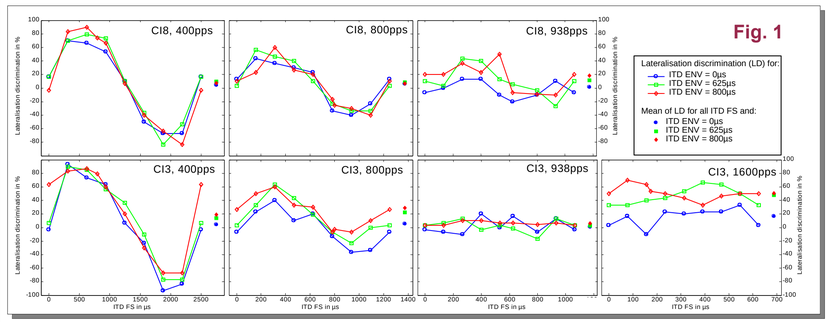
- Definitions of ITD conditions:
  - ENV: ITD information in the envelope, ITD FS = 0µs
  - WD: waveform delay, equal ITD information in both envelope and fine structure
- Independent variables (conditions):
  - Pulse Rates: 100 to 1600pps, corresponding to the Inter Pulse Interval (IPI) of 10ms to 625µs; preselected for each subject according to his/her sensitivity
  - ITD ENV: 0, 625 and 800µs for CI listeners and 0, 400 and 625µs for NH
  - ITD FS: 0 to IPI in steps of 1/8 IPI

4. Procedures

- Lateralization discrimination task using a 2 interval, 2AFC paradigm:
  - Constant stimuli method: randomization of items in block of constant pulse rates
  - Intervals: 1) reference stimulus without ITD, 2) target stimulus with ITD
  - 60 repetitions for each condition (border of significance: ±20%)
  - Response of subject mapped from percent correct [0...100%] to lateralization discrimination (LD) [-100...+100%]
- Binaurally balanced, pitch matched electrode pair as a result of following pretests:
  - Simple fitting procedure to estimate the comfortable level (CL)
  - Binaural balancing procedure to iterative determine binaurally loudness balanced levels for each electrode pair
  - Pitch ranking procedure implemented as a 2 AFC pitch discrimination paradigm

5. Stimulus presentation

- CI listeners: Direct stimulation with interaurally synchronized electrical amplitude modulated pulse trains, interaural synchronization accuracy better than 2.5µs
- NH listeners: Simulation of CI-stimulation presented via headphones in double walled sound booth:
  - Monophasic pulse trains (pulse duration: 10µs) filtered with Butterworth filter (8th order, center frequency: 4650Hz, bandwidth: 1500Hz)
  - Constant level of stimulation: 60.8dB SPL(A) RMS



Tab. 1. Bibliographic data of CI listeners

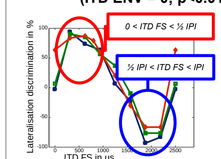
Subject	*Aetiology*	*Age at implantation*		*Deafness duration*		*binaural electr. stim. experience*
		L	*R*	*L*	*R*	
CI1	Meningitis	14 yr	14 yr	5.5 mo	1.5 mo	6 yr
CI2	Skull trauma	54 yr	48 yr	21yr	25 yr	4 yr
CI3	Meningitis	21 yr	21 yr	2 mo	2 mo	1 mo
CI8	Osteogenesis imperfecta	41 yr	39 yr	3yr	12 yr	2 mo

RESULTS

Subjects:

- Homogeneous NH listener group (p=0.995), see **Fig. 3**
- Non homogeneous CI listener group (p=0.001), see **Fig. 1** and **Fig. 2**
- Results of better performing CI listeners (CI3 and CI8) are homogeneous with NH listeners results (p=0.995)

Fig. 4: Maximal pulse rate with effect of ITD FS on LD (ITD ENV = 0; p<0.01)



Subject	Max. pulse rate
NH	600 pps
CI1	200 pps
CI2	200 pps
CI3	800 pps
CI8	800 pps

Interaural synchronization of fine structure (ITD FS = 0):

- Synchronization of fine structure is necessary if LD depends on ITD FS
  - Two groups: 1) all LDs for 0 < ITD FS < ½ IPI; 2) all LDs for ½ IPI < ITD FS < IPI. LDs for ITD FS = 0 and ½ IPI were discarded. See **Fig. 4**
  - If there is a significant difference (p<0.05) between the LD for these groups, LD depends on ITD FS
  - Only data for ITD ENV = 0 were taken into account
- **Fig. 4** shows the maximal pulse rate with significant effect of ITD FS on LD

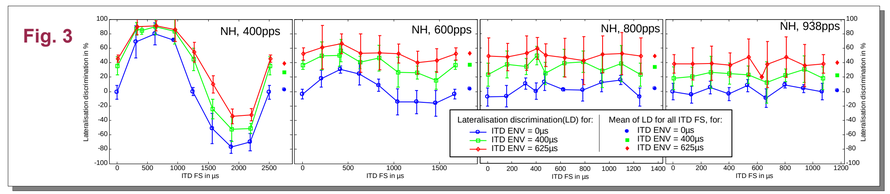
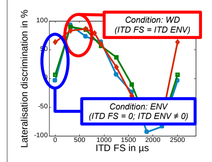


Fig. 5: Maximal pulse rate with improvement of LD by synchronizing ITD FS to ITD ENV (p<0.05)



Subject	Max. pulse rate
NH	600 pps
CI1	200 pps
CI2	100 pps
CI3	400 pps
CI8	400 pps

Synchronization of ITD FS to ITD ENV

- Analysis: Comparison of LDs between conditions WD and ENV
- Results: Maximal pulse rate with significant improvement (p<0.05) of LD for WD condition for NH listeners and each CI subject, see **Fig. 5**

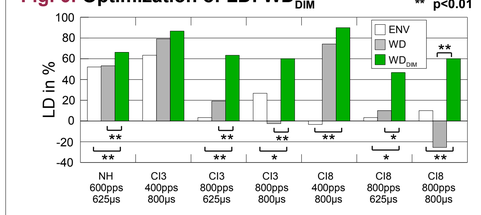
Optimization of synchronization

- Problem: for higher pulse rates and ITD values the ITD ENV and ITD FS cues may favor different lateral directions.
- Solution: diminish the ITD FS value to ¼ IPI:

$$ITD\,FS = min(ITD\,ENV\,,\,1/4\,IPI)$$

- We call the optimized synchronization *diminished waveform delay* (**WD_{DIM}**)
- Results: **Fig. 6** shows the effects of condition WD_{DIM} compared to conditions ENV or WD. Improvement was achieved in most cases, in one case (CI8, 800pps, 800µs) even a reversal of lateralization could be achieved.

Fig. 6: Optimization of LD: WD_{DIM}



CONCLUSIONS

- **CI listeners are sensitive to fine structure ITD**
  - Better performing CI listeners for pulse rates up to 800pps
  - NH subjects comparable to the better performing CI listeners
- **Synchronization of envelope and fine structure ITD improves lateralization discrimination**
  - better performing CI listeners for pulse rates up to 400pps
  - the improvement breaks down for higher ITD values and higher pulse rates
- ***Diminished waveform delay*** **(WD_{DIM}) improves lateralization discrimination for pulse rates up to 800pps and higher ITD values**

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We thank the CI listeners for their enthusiastic participation in this study.
The equipment for direct electrical stimulation was provided by MED-EL Corp.
This research was supported by the Austrian Academy of Sciences