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Short Report

Temporal loudness integration at threshold in cochlear implant users: A study on the critical duration and the effects of a very high stimulation rate

Lautheitsintegration an der Hörschwelle bei Cochlea-Implantat-Nutzern: Eine Studie zur kritischen Dauer und den Auswirkungen einer sehr hohen effektiven Stimulationsrate

Carmen Marie Castañeda González[1]
Daniela Schwanda[1,2]
Miguel Obando Leitón[1]
Sonja Karg[3]
Werner Hemmert[1]

1 Technical University of Munich, Munich Institute of Biomedical Engineering, Bio-Inspired Information Processing, Garching near Munich, Germany

2 Munich University of Applied Sciences, Department of Applied Sciences and Mechatronics, Munich, Germany

3 Technical University Ingolstadt, Biomedical Engineering and Biosignal Processing, Ingolstadt, Germany

Abstract

Detection thresholds (DTs) decrease with increasing stimulus duration. This phenomenon is known as temporal loudness integration (TLI). In normal hearing (NH), DTs improve by 6.7 dB/decade up to a critical stimulus duration (t_{crit}) of approximately 200 ms (Heil et al. 2017, Zwislocki 1969). In this study, TLI was investigated in seven cochlear implant (CI) users (MED-EL) using direct stimulation at a clinical and at a higher stimulation rate (1.2 and 25 kpps) at two electrode positions (apical, basal). Stimulus durations ranging from a single pulse (15 µs phase duration) to 1.5 s long pulse trains were tested to determine the critical duration t_{crit} above which DTs are independent of stimulus duration.

At a constant stimulation rate, DTs decreased with increasing stimulus duration. On average, no systematic effect of the electrode position was observed. Critical durations in CI users (t_{crit}=244±136 ms) were similar to critical durations in NH, and were independent of the electrode position and the stimulation rate. For two subjects, it was not possible to determine a critical duration t_{crit} at 25 kpps. The stimulation rate influenced the slope of the TLI. TLI curves were steeper at 25 kpps (−6.2±0.9 dB/decade) than at 1.2 kpps (4.1±1.3 dB/decade). Surprisingly, the TLI slope of CI users at high stimulation rates was comparable to NH values, although the nonlinear compression in the inner ear is missing in electrical stimulation. Therefore, our data shows that, at high stimulation rates, TLI curves in electric hearing are similar to acoustic ones, despite the missing non-linear compression in the intact ear. The stimulation rate influenced the steepness of the TLI curves, which in turn affects the CI user's perception of long and short sounds.

Keywords: loudness integration, cochlear implants, psychoacoustics, critical duration, high stimulation rate

Zusammenfassung

Die sogenannte Lautheitsintegration (LI) benennt den Effekt, dass mit zunehmender Dauer eines Reizes die entsprechende Hörschwelle sinkt. Bei Normalhörenden (NH) verbessert sich hierbei die Hörschwelle um 6,7 dB/Dekade bis zu einer kritischen Dauer (t_{krit}) von 200 ms (Heil et al. 2017, Zwislocki 1969). In dieser Studie wurde die LI von sieben Cochlea-Implantat(CI)-Nutzern (MED-EL) an zwei Elektrodenpositionen (apikal, basal) über Direktstimulation bestimmt, jeweils bei einer klinischen und einer höheren Stimulationsrate (1,2 und 25 kpps). Hörschwellen bei Stimulusdauern zwischen einem einzelnen Puls (15 µs Phasendauer) und bis zu 1,5 s langen Pulsfolgen wurden gemessen, um die kritische Dauer t_{krit} zu bestimmen, ab der die Hörschwelle unabhängig von der Stimulationsdauer ist.

Bei konstanter Stimulationsrate nahmen die Hörschwellen mit zunehmender Stimulusdauer ab. Im Mittel wurde kein Einfluss der Elektrodenposition auf die LI-Charakteristik festgestellt. Kritische Dauern von CI-Nutzenden (t_{krit}=244±136 ms) ähnelten kritischen Dauern von NH und waren unabhängig von der Elektrodenposition und der Stimulationsrate. Bei zwei Probanden war es nicht möglich, eine kritische Dauer t_{krit} bei 25 kpps zu bestimmen. Die Steilheit der LI-Kurven war von der Stimulationsrate abhängig: LI-Kurven waren bei 25 kpps steiler (–6,2±0,9 dB/Dekade) als bei 1,2 kpps (–4,1±1,3 dB/Dekade). Es überrascht, dass die LI Steilheit von CI-Nutzenden bei hohen Stimulationsraten vergleichbar mit NH Werten war, obwohl die nichtlineare Kompression im Innenohr bei elektrischer Stimulation fehlt. Daher können die flachen LI-Kurven im elektrischen Hören nicht ausschließlich durch den Verlust der nichtlinearen Kompression erklärt werden. Stattdessen beeinflusste die Stimulationsrate die Steilheit der LI-Kurven, was sich wiederum auf die Wahrnehmung langer und kurzer Töne auswirkt.

Schlüsselwörter: Lautheitsintegration, Cochlea-Implantate, Psychoakustik, kritische Dauer, hohe Stimulationsrate

1 Introduction

Listeners perceive short stimuli quieter than long stimuli at the same stimulus intensity. This effect is called temporal loudness integration (TLI). Conversely, at the hearing threshold, short stimuli require higher amplitudes than long stimuli to be perceived. In normal hearing (NH), the detection threshold (DT) drops by 6.7 dB upon a tenfold increase in stimulus duration (decade) [1]. This improvement in DT holds up to a critical duration t_{crit} of 200 ms [2]; for longer stimuli, the DT becomes independent of stimulus duration.

The effect of TLI has also been observed in cochlear implant (CI) users [3], [4]. At a fixed stimulation rate, DTs decrease with increasing stimulus duration, i.e., as the number of pulses in a pulse train increases. However, the improvement in DTs is significantly lower than in NH (–1.4 dB/decade [3]). TLI has mainly been investigated for single-channel stimulation rates between 300 and 3,000 pps (pulses per second) and stimulus durations up to 300 ms [4], [5], [6]. Literature on TLI at longer durations reported inconsistent results on a possible critical duration in electric hearing. While in [3], critical durations of around 100 ms were found only in some subjects, [7] reported critical durations comparable to NH between 50 and 200 ms, and [8] reported critical durations around 100 ms. Our study set out to find the slope and critical durations for a clinically used single-channel stimulation rate (1.2 kpps) and for a high stimulation rate (25 kpps). Characterizing TLI curves at high stimulation rates is relevant since the coding strategies activate multiple contacts in quick succession. Systematically reviewing the effects of an overall increased stimulation rate may lead to improved coding strategies that provide normal-hearing TLI characteristics and reduce the unpleasant loud distortions known to be a common problem for CI users.

Due to the wide current spread in the cochlea when stimulated with a CI [9], [10], [11], the effective stimulation rate to which a nerve fiber is exposed can correspond to the summed rate of several active electrodes. Therefore, two stimulation rates were selected for this study: (1) a single-channel HDCIS (High-Definition Continuous Interleaved Sampling) stimulation rate of 1.2 kpps and (2) a stimulation rate of 25 kpps. TLI was measured at threshold in seven CI users at two stimulation rates (1.2 kpps and 25 kpps) and two electrode positions (apical and basal) using the adjustment method. Stimulus durations from a single pulse (15 µs phase duration) to 1.5 s long pulse trains were tested to determine the critical duration (t_{crit}) from which on DTs are independent of stimulus duration.

2 Methods

2.1 Subjects and stimuli

Seven CI users (4 female, 3 male, 8 ears) between 17 and 82 years (mean age: 59±21 years) participated in this study. All subjects had MED-EL implants (products: Sonata, Synchrony, Pulsar, Concerto) and at least one year of CI experience. Subjects gave their informed written consent and received monetary compensation. This study was conducted in accordance with the Declaration of Helsinki and approved by the medical ethics committee of the Klinikum Rechts der Isar (Munich, 2126/08).

Stimuli programmed with MATLAB were sent directly to the electrode array using MED-EL's MAXBOX, bypassing the speech processor. TLI was examined at two stimulation rates (1.2 and 25 kpps) on an apical (E3) and a basal electrode (E10 out of 12 electrodes in MED-EL CIs). Stimuli were pulse trains of biphasic cathodic-leading pulses with 15 µs phase duration and 2.1 µs interphase gap. The duration of the pulse trains ranged from a single pulse to 1.5 s (1,800 pulses at 1.2 kpps and 37,500 pulses at 25 kpps). There were 11 durations measured at 1.2 kpps and 15 durations at 25 kpps, including the single pulse condition. The pulse train containing a single pulse was measured once and assigned to both stimulation rates. During the experiment, the stimulus repeated after a 500 ms pause.

2.2 Procedure

Subjects adjusted the stimulation amplitude to their DT using a keyboard (adjustment method); stimulus amplitudes could be changed in fine and coarse steps. Subjects familiarized themselves with the task during a single training round. Four well-separated DTs (single pulse, 10 ms, 100 ms, and 1.5 ms), five at the higher rate ((single pulse), 1 ms, 10 ms, 100 ms, and 1.5 s), were measured during training at both electrode positions. DT estimates for the remaining durations were linearly interpolated in the log-log domain to speed up the measurement time during the main experiment. Training trials were not randomized; DTs were measured from the longest to the shortest duration, one rate and one electrode at a time.

The main experiment consisted of four repetitions of all possible combinations: electrode x stimulation rate x duration (50 conditions). Each round contained all 50 conditions in randomized order. To minimize biases, DTs were adjusted starting twice from below and twice from above the DT amplitude [12]. If subjects did not request a break before, breaks were programmed every 25 min.

Slopes and critical durations were estimated by fitting the data to a broken stick curve of the form:

$$I = \begin{cases} I_1 \cdot N^m & , N < N_{crit} \\ I_\infty & , N \geq N_{crit} \end{cases}$$

With I being the DT amplitude in CU (current unit, 1 CU corresponds to approximately 1 µA), I_1 the stimulus amplitude for the single-pulse condition, N the number of pulses, m the slope, N_{crit} the critical duration in number of pulses, and I_∞ the asymptote value after the critical duration has been exceeded. An exemplary fit for subject S3 (25,000 pps, apical electrode) is shown in Figure 1. On a double-logarithmic axis, power functions appear as a linear dependency (see Figure 2). Power law fits have already been used to describe NH [13] and CI data [5]. Fits worked well with R^2=0.97±0.02 and R^2=0.98±0.01 at 1.2 kpps for the apical and basal electrode, respectively, and R^2= 0.99±0.01 and R^2=0.99±0.01 at 25 kpps.

3 Results

Figure 2 shows the DTs with regard to the DT amplitude of a single pulse (SP DT) as a function of stimulus duration. The black dotted line denotes NH TLI characteristics [1], [2]. TLI was observed at both stimulation rates and electrodes; DTs decreased with increasing stimulus duration up to 244±136 ms and remained unchanged at longer stimulus durations. On average, no systematic effect of the electrode (apical, basal) was observed. In contrast, TLI was affected by the stimulation rate; TLI curves were steeper at the higher stimulation rate. At 1.2 kpps, DTs decreased with increasing stimulus duration by 4.1±1.3 dB/decade up to t_{crit}=206±103 ms (Figure 2, left panel). At 25 kpps, DTs improved by 6.2±0.9 dB/decade (t_{crit}=291±182) (Figure 2, right panel) and resembled NH TLI (black dotted line). Neither the electrode nor the stimulation rate affected the critical duration. Increasing the stimulation rate from 1.2 kpps to 25 kpps, which corresponds to increasing the number of pulses within a fixed period of time, also decreased DTs. Although related to TLI, this is a different effect known as multi-pulse integration [4], [14].

TLI showed high intersubjective variability. TLI slopes at 1.2 kpps ranged from –2.2 dB/decade (S1) to –7.8 dB/decade (S8), the latter even exceeding slopes reported in NH. Interestingly, S8's slope did not increase further at 25 kpps (–7.2 dB/decade). Slopes at 25 kpps ranged between –4.6 dB/decade (S4) and –7.5 dB/decade (S1). Except for S8, all subjects exhibited steeper slopes at the higher stimulation rate, and five out of eight subjects had slopes comparable to, or larger than, NH values (>6 dB/decade). Critical durations were between 33 ms (S4) and 751 ms (S2). For two subjects (S5 and S7), no critical duration t_{crit}<1.5 s could be determined at the higher rate. Although, on average, the electrode had no systematic effect on the TLI curves, S4 exhibited shorter critical durations at the basal electrode position, e.g., 352 ms (apical, 1.2 kpps) compared to 33 ms (basal, 1.2 kpps).

4 Discussion

The slope at which DTs improved with increasing stimulus durations was –4.1±1.3 dB/decade at 1.2 kpps and –6.2±0.9 dB/decade at 25 kpps. These slopes are larger than the –0.42 dB per doubling of duration, equivalent to –1.4 dB/decade, reported for a 100 pps stimulation rate [3]. The slope for 1.2 kpps is similar, if not somewhat higher, than the –3.5 dB/decade slope for 1.5 kpps stimuli in [5]. The mean slope of –6.2 dB/decade at 25 kpps is fittingly higher than slopes found for 10 kpps (–4.3 dB/decade [15]) and 18 kpps (–5.5 dB/decade [5]). As reported by other studies [4], [5], [16], we also observed highly intersubjective variable TLI slopes. Our critical durations (1.2 kpps: 247±123 ms; 25 kpps: 292±182 ms) were comparable to, and higher than, values cited in the literature for electric hearing (100 ms [3], [8]; 50–200 ms [7]) and NH (200 ms [2]). In agreement with [5], [16], no systematic effect of the electrode was observed on average. However, two subjects exhibited noticeable differences between electrodes in accordance with [3], [5], [14]. These differences within a single subject might be explained by neuronal health at that specific location, proximal to the stimulation site [4], [14]. Despite several studies suggesting that a central process mediates TLI [8], [15], [17], [18], the integration of auditory information seems to have important peripheral processing components. It has been hypothesized that

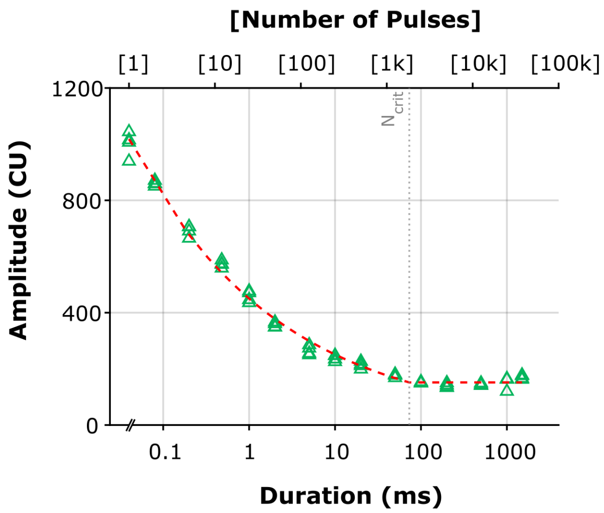

Figure 1: Fit for the temporal loudness integration (TLI) curve for S3 at threshold (25 kpps, apical electrode; R^2=0.99). Detection threshold (DT) plotted as amplitudes in CU (current unit, 1 CU is roughly equivalent to 1 µA). Stimulus duration in number of pulses (upper axis) and corresponding duration in milliseconds (lower axis). The lower axis was cut to accommodate the single pulse condition, for which a pulse train duration (in ms) cannot be assigned unambiguously. The vertical dotted line denotes the critical duration N_{crit} above which the amplitude remains unchanged (I_{∞}).

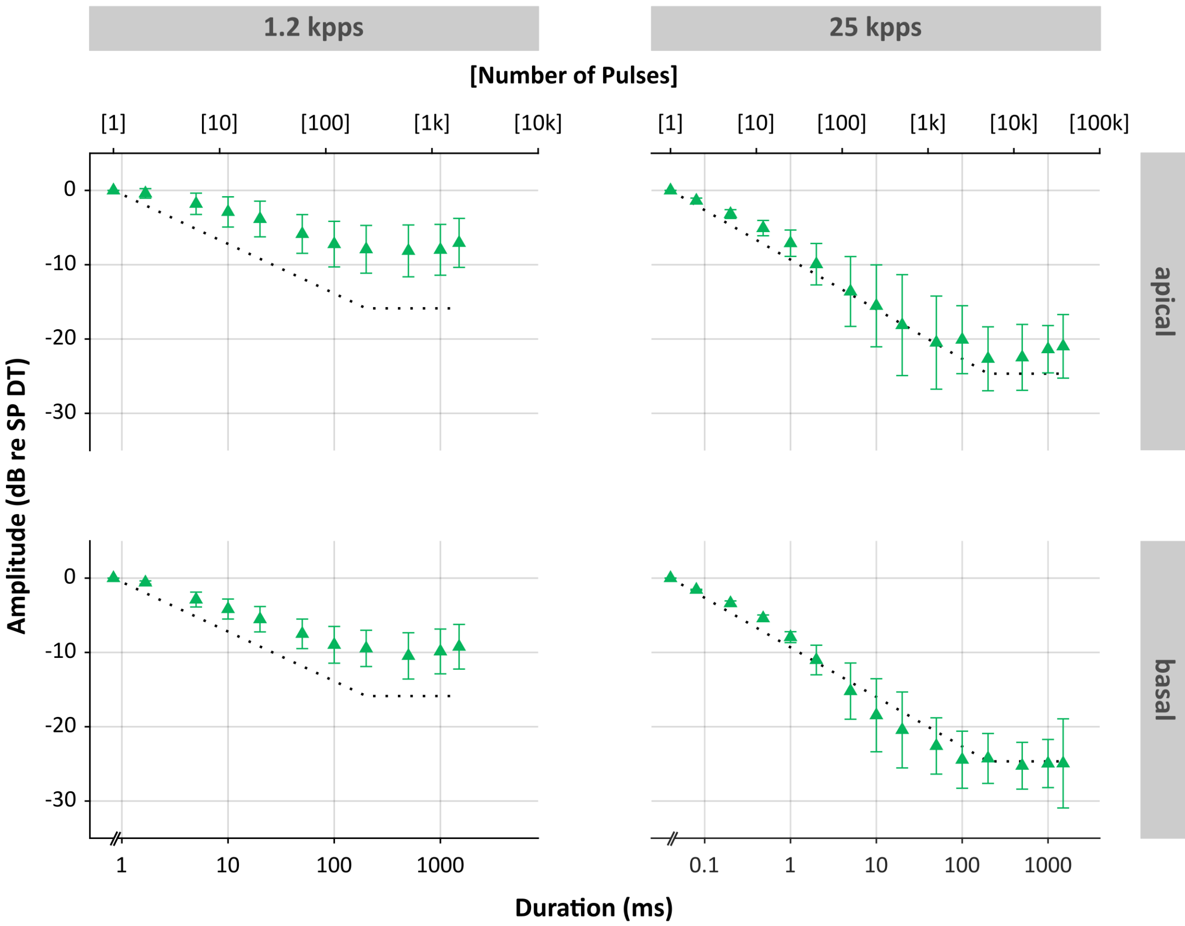

Figure 2: Temporal loudness integration (TLI) at threshold (mean ± standard deviation, n=8). Detection threshold (DT) amplitudes in dB re single-pulse detection threshold (SP DT) of the corresponding electrode. Stimulus duration in number of pulses (upper axis) and corresponding duration in milliseconds (lower axis). The lower axis was cut to accommodate the single pulse condition, for which a pulse train duration (in ms) cannot be assigned unambiguously. The dotted line shows the average TLI in normal hearing with a slope of 6.7 dB/decade and a critical duration of 200 ms. Top: Apical electrode. Bottom: Basal electrode. Left: 1.2 kpps. Right: 25 kpps.

TLI slopes are influenced by the nonlinear compression in the inner ear and, therefore, shallow slopes in hearing-impaired listeners (2–3 dB/decade [19]) are due to the loss of compression in the hearing-impaired ear [20]. It is thus surprising that the TLI slopes at 25 kpps (–6.2 dB/decade) are comparable to NH values (–6.7 dB/decade), even though the nonlinear compression in the inner ear is missing in electric hearing. Even more so, S8 had a slope of –7.8 dB/decade already at 1.2 kpps. Other factors affecting the steepness of TLI slopes include the abnormally rapid increase in neural firing rate with stimulus level [3], [17], [19], [21], rapid and high adaptation to electrical stimulation [4], [21], and neural health [4], [22].

Our measurements provide new insights into how auditory information is integrated in the auditory system, especially for electrical hearing with a CI. Our data shows that, at high stimulation rates, TLI curves in electric hearing are similar to acoustic ones, despite the missing non-linear compression in the intact ear. The stimulation rate influenced the steepness of the TLI curves, which in turn will affect the CI user's perception of long and short sounds. As the speech processor and its coding strategy also influence the TLI in CI users, it remains to be investigated how the coding strategy affects TLI and whether steeper TLI curves are beneficial for speech understanding, e.g., for detecting weak consonants of short duration (p, t, k). Restoring natural TLI in CIs is essential for an accurate loudness representation, particularly for the perception of short, impulsive sounds, to avoid unpleasantly loud stimuli.

Notes

Conference presentation

This contribution was presented at the 26th Annual Conference of the German Society of Audiology and published as an abstract [23].

Acknowledgments

We are particularly grateful to the seven study participants.

MED-EL (Innsbruck) and the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) [project number 415658392] funded this project.

Competing interests

The authors declare that they have no competing interests.

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Corresponding author:

Carmen Marie Castañeda González
Technical University of Munich, Munich Institute of Biomedical Engineering, Bio-Inspired Information Processing, Boltzmannstraße 11, 85748 Garching, Germany

Please cite as

Castañeda González CM, Schwanda D, Obando Leitón M, Karg S, Hemmert W. Temporal loudness integration at threshold in cochlear implant users: A study on the critical duration and the effects of a very high stimulation rate. GMS Z Audiol (Audiol Acoust). 2024;6:Doc13. DOI: 10.3205/zaud000048, URN: urn:nbn:de:0183-zaud0000481

This article is freely available from

https://doi.org/10.3205/zaud000048

Published: *2024-09-10*