1 **Title: Integration of temporal masking into the MP3000**
2 **Coding strategy**

3

4 Authors:

5 Dr. Eugen Kludt

6 Department of Otolaryngology

7 Medical University of Hannover

8 Phone: +49 511 5326906

9 kludt.eugen@mh-hannover.de

10

11 Prof. Dr.-Ing Waldo Nogueira

12 Department of Otolaryngology

13 Medical University of Hannover

14 and Hearing4all

15

16 Prof. Dr. Thomas Lenarz

17 Department of Otolaryngology

18 Medical University of Hannover

19

20 Prof. Dr. Andreas Büchner

21 Department of Otolaryngology

22 Medical University of Hannover

23 and Hearing4all

24

25

26 (f) sources of support that require acknowledgment;

27

28 Hearing4all

29

Abstract

Objective: Evaluation of speech intelligibility benefit by addition of a temporal masking model to the MP3000 speech coding strategy.

Study Design: A crossover design was used to compare variants of the new temporal masking strategy TPACE with respect to the clinical MP3000 strategy.

Setting: The study was a prospective, within-subject, repeated-measure experiments.

Patients: The study group consisted of 24 postlingually deaf subjects with a minimum of six months experience after CI activation.

Intervention: Five conditions were evaluated: The original MP3000 algorithm and the TPACE with four different settings of the temporal masking parameter.

Main Outcome Measures: Speech perception test in Comité Consultatif International Téléphonique et Télégraphique (CCITT) noise at 15 to 5 dB SNR.

Results: Average speech intelligibility improved with TPACE ($T_{\frac{1}{2}} = 0.5$ ms) by 10 % to 11% compared to MP3000.

Conclusion: The addition of temporal masking to the simultaneous masking model of MP3000 could improve the speech intelligibility in noise

Key Words: Speech coding strategy – Temporal masking – Psychoacoustic model

Introduction

Cochlear implants (CI) restore functional hearing in subjects with severe to profound hearing loss, but despite the enormous success and recent advancements, users of these devices still have extensive problems to understand speech in challenging environments such as background noise or reverberation. Generally, CIs consist of an externally worn sound processor and an implant connected to an electrode array carrying up to 22 electrode contacts. The electrode array is positioned inside the scala tympani for the purpose of electrically stimulating neural elements in the cochlear modiolus. The sound processor is responsible for decomposing the audio signal into different frequency bands or channels and determining the signal amplitudes in these bands. Each of these channels corresponds to one intra-cochlear electrode contact to which appropriate electrical currents proportional to the band-pass amplitudes are applied. A detailed and comprehensive description of this process and the different sound coding strategies can be found in [1,2].

One factor that restricts speech intelligibility is the relatively crude interface between the CI electrodes and the auditory nerve (e. g. [3,4]). Electrical stimulation

inside the fluid-filled cochlea leads to significant current spread reducing the number of independent channels in the cochlea. As reviewed in Richter et al. [5], only 4 to 7 intracochlear electrode contacts of today's implants can be considered independent, while normal hearing subjects can process 30–50 independent channels. As a result, the amount of information, which can be conveyed towards higher processing stages in the auditory system is significantly reduced.

One possible approach to improve the speech intelligibility performance of the patients is to identify perceptually relevant signal components and concentrate on their presentation [6]. The rationale here is to reduce the number of stimuli being sent through the electrode-nerve-interface, implicitly also reducing channel interaction due to the sparser coding of the acoustic signal. Forerunner strategies of this principle have been the so called n-of-m strategies. The n-of-m strategy estimates the envelope amplitude for each of the m bandpass filters in the system (one for each channel), and selects the n channels with the largest amplitude for stimulation. Therefore, in any period only n channels execute stimulation pulses to their respective electrode contact. Especially in the earlier days of cochlea implantation, this simple maxima selection was particularly used to increase the temporal resolution of selected channels, as the implant hardware typically was too slow to stimulate all intra cochlear electrodes for each processing frame [7]. The PACE (Psychoacoustic Advanced Combination Encoder) strategy modifies this maxima selection algorithm with a psychoacoustic model that employs simultaneous masking to select the perceptually relevant channels for stimulation [6,8]. The results with this new strategy, which was clinically released under the

97 name of MP3000, were encouraging [9]. It was possible to reduce the number of
98 stimulated electrodes and preserve the same level of speech intelligibility as with
99 the clinical default strategy ACE (Advanced Combination Encoder) on the Cochlear
100 Nucleus 24 device. The new strategy successfully reduced the energy consumption
101 due to the reduced number of stimuli, the performance of the patients however was
102 not further improved over that with the ACE strategy [6,8].

103

104 A novel CI coding strategy that adds a model of temporal masking to the PACE
105 speech coding strategy has been designed. The new strategy, termed the temporal
106 psychoacoustic advanced combination encoder (TPACE) follows the principle of
107 removing unnecessary information to further take load off the limited electrode-
108 nerve interface. In the new strategy, the algorithm for channel selection was
109 extended by incorporating a temporal masking model additionally to the
110 simultaneous masking concept. Although the simultaneous masking is considered
111 the most dominant masking effect in the field of perceptual audio coding, temporal
112 masking – particularly post-masking or forward masking - does also play a
113 significant role and is implemented in many data compression algorithms for audio
114 signals [10]. For practical reasons, we only considered forward masking in our
115 implementation, as the use of backward masking is hardly possible in real-time
116 audio processing. We focused on the peripheral effect of the absolute and relative
117 refractory recovery of spiral ganglion neurons with time constants equal or below
118 1.1 ms, which covered the range of previously reported recovery function time

constants [11,12], while temporal masking in normal hearing subjects can last up to 200 ms.

The concern with longer time constants was that the stimulation patterns would change too drastically, subsequently short constants in the single digit range were selected, based on the electrograms by visual inspection. Our goal was to compare the speech intelligibility outcomes of the new TPACE with respect to the existing MP3000 strategy in CI subjects. Furthermore, we evaluated whether there is a relationship between the refractoriness of the auditory nerve fibers measured by Neural Response Telemetry (NRT) and different slopes of masking decay used in the TPACE implementation. It is known that there is individual variation in refractory period across CI subjects and a relationship between the masking time constants and the neural refractory period might potentially allow for a patient-specific individualization of the temporal masking behavior within the new TPACE strategy.

Materials and Methods

Study Participants.

The study group consisted of 24 postlingually deaf subjects with a minimum of six-months experience with the Nucleus CI system (Table 1). All subjects used either ACE or MP3000 strategy in daily life and were at least able to understand speech in quiet.

138

139 **Review of the electrode selection in the MP3000 strategy.**

140 The channel selection algorithm of the MP3000 strategy incorporates a
141 psychoacoustic model that considers simultaneous masking to select channels for
142 stimulation. Details can be found in [8], but a brief description of the basic principle
143 shall be given here. Implementation of the strategy has been done using the NIC
144 (Nucleus Implant Communicator) development environment Version 2. A block
145 diagram illustrating the MP3000 coding strategy is presented in Figure 1. The digital
146 audio signal, sampled at $F_s = 16$ kHz, is analyzed in frames of 128 samples and
147 converted into the frequency domain using a fast fourier transform (FFT). Next, the
148 amplitude envelope $A(z)$ in each of the 22 frequency bands ($z = 1, \dots, M$) is computed
149 combining the energy of the according FFT bins. The channel selection algorithm is
150 then applied iteratively until the desired number of bands is reached, as follows: For
151 the first channel selection, simply the band with the highest amplitude with respect
152 to the threshold of audibility is picked for stimulation, as there is obviously no
153 simultaneous masking across channels beforehand. For the selection of the
154 remaining channels within the same processing frame, the simultaneous masking
155 model is being used, picking the channel affected by the least amount of masking.
156 After each band selection, the masking profile, i.e. the threshold of perception across
157 all bands, is updated accordingly, obviously based on the channels which have been
158 already selected. When all channels of one processing frame have been selected, the

159 masking profile is set to zero and the process of channel selection starts from
160 scratch.

161

162 **Implementation of TPACE strategy**

163 TPACE introduces forward masking by carrying over the final masking profile from
164 the preceding processing frame, instead of starting from scratch, i.e. the threshold of
165 perception from frame n does not start from zero, but inherits the attenuated
166 simultaneous masking thresholds from frame $n-1$ for all 22 channels. Subsequently,
167 for the selection of the first band in frame n , the band with the strongest signal
168 above the inherited masking threshold is selected. After that, similar to the MP3000
169 strategy, the masking profile is updated, considering the already selected channels
170 in frame n and the attenuated masking thresholds of frame $n-1$. The process of
171 channel selection is then repeated until the desired number of channels has been
172 reached.

173 The strength of temporal masking in TPACE is determined by the temporal masking
174 half-life $T_{1/2}$ (Figure 2). This time constant indicates after which time the strength of
175 the temporal masking has decreased to half of the amount of the initial masking at
176 the time T_0 . As in TPACE the final masking profile of the preceding frame is being
177 carried over (see above), the masking profile at the time T_0 would exactly resemble
178 the masking profile of the preceding frame. Goal is to make the slopes shallower
179 across time such that different bands are selected. This is implemented applying a

factor F in the dB domain. According Nogueira et al. [8] Eq. 7 the masking level in each band z and frame n denoted by $L_{Tn}(z)$ in dB:

$$(1) L_{Tn}(z) = F \cdot L_{Tn-1}(z).$$

To initialize the thresholds for a given frame, the attenuation factor F , which is applied to the masking threshold of the preceding frame, can be calculated from the stimulation rate $(1/t)$ where t denotes the time variable in seconds and temporal masking half-life $T_{1/2}$ using the following equation:

$$(2) F = 2^{-\frac{t}{T_{1/2}}}.$$

The effect of $T_{1/2}$ on the channel selection is presented in the electrodiagrams of Figure 3. Short $T_{1/2}$ cause a fast decay of the temporal masking. For values of 0.2 ms and below, the channel selection within the psychoacoustic model is hardly influenced by temporal masking, leading to an electrodiagram that resembles the one of the MP3000 sound coding strategy. With longer $T_{1/2}$ values, temporal masking has more and more effect on the channel selection and the differences to the MP3000 algorithm become clearly visible at $T_{1/2} = 0.5$ ms. Values of $T_{1/2}$ above 1.1 ms further increase the impact of temporal masking, leading to strong redistribution of stimulation to regions with very low signal amplitudes. Therefore, $T_{1/2}$ values of 0.5 and 1.1 ms were selected for the first evaluation of speech intelligibility in CI users.

Furthermore, two additional $T_{\frac{1}{2}}$ values of 0.4 and 0.8 ms were evaluated in a follow-up experiment.

Evaluation TPACE in Acute Streaming Experiments

The TPACE algorithm was implemented using the Nucleus MATLAB Toolbox (Cochlear Ltd., Sydney, Australia) and the Nucleus Implant Communicator (NIC) research interface (Cochlear Ltd., Sydney, Australia) was used for two acute streaming experiments using the L34 research speech processor (Cochlear Ltd., Sydney, Australia).

In the first experiment, twelve subjects (P1.1 to P1.12, Table 1) were tested in one single session using Hochmair-Schulz-Moser (HSM) sentences [13] in noise in three conditions: TPACE using $T_{\frac{1}{2}}$ of 0.5, 1.1 ms and the original MP3000 algorithm. In a second experiment, twelve other subjects (P2.1 to P2.12, Table 1) were tested in a single session with HSM sentences in noise in five conditions: TPACE using $T_{\frac{1}{2}}$ of 0.4, 0.5, 0.8, 1.1 ms and the original MP3000 algorithm.

Subjects who used the ACE strategy in their daily life were fitted with MP3000. All streaming experiments were performed with 900 pps and 5 maxima. In order to avoid ceiling effects, a pilot testing with the HSM sentence test at 10 dB SNR was performed. Subjects that scored more than 80% or less than 20% were tested at 5 dB SNR or 15 dB SNR respectively (Table 1, tested SNR). A single-subject repeated-measure design with an ABCDE-EDCBA testing sequence was used. Each subject

served as her or his own control. Statistical analysis was performed with the Quade Test [14].

Neural Response Telemetry

The measurement of the electrically evoked compound action potential (ECAP) recovery functions was performed using Custom Sound EP software (Cochlear Ltd., Sydney, Australia) with a method described by Miller et al. [15] in subjects taking part in the second experiment. Apical, medial and basal electrodes (5, 12 and 20) were measured. The masker probe interval (MPI) was varied between 300 μ s and 10 ms in these measurements. An exponential function shown in equation (2) was fitted by the Custom Sound EP software to get the saturation level A , absolute refractory period T_0 and a measure of the relative refractory period τ (Figure 4).

$$(3) \quad ECAP(MPI) = A(1 - \exp(-(T_0 - MPI)/\tau)). [\mu V]$$

Spearman correlation was calculated between the rank of refractory period measures (T_0 , τ) and the masking half-life constant $T_{1/2}$ which achieved best performance for each individual subject.

243

244 **Results**

245 Figure 5 presents the speech intelligibility results as difference score obtained with
246 MP3000 and TPACE averaged for each subject. Overall, median speech intelligibility
247 in noise was better with TPACE using $T_{1/2} = 0.5$ ms than with the MP3000 by 11 % in
248 the first (significant with $p < 0.05$) and by 10 % in the second study (Figure 5).

249 Further increase of the temporal masking half-life $T_{1/2}$ led to a decrease of speech
250 intelligibility benefit. However, results of individual speech intelligibility presented
251 in Figure 6, indicate an optimal $T_{1/2}$ between 0.4 and 0.8 ms or even without any
252 temporal masking.

253 The recovery time constants that were derived from the measurement of the
254 recovery functions were $T_0 = 0.48 \pm 0.13$ ms and $\tau = 0.81 \pm 0.25$ ms. No significant
255 correlation between the rank of the individual recovery time constants and the
256 optimal masking half-life constant of the subject was found.

257 However, a comparison between the clinical performance of the subjects and their
258 benefit using TPACE with $T_{1/2} = 0.5$ ms indicates that subjects with above-average
259 speech intelligibility in their clinical records benefit more from the temporal
260 masking than subjects with worse results during their clinical routine (Figure 7).

261

262

Discussion

This work presented a novel CI sound coding strategy that adds a model of temporal masking to the PACE speech coding strategy. The temporal masking model is parameterized through a time constant that mimics the refractory time of the auditory nerve. The results from this study indicate that the incorporation of temporal masking with a time constant $T_{1/2}$ of 0.5 ms into the sound coding strategy can improve speech intelligibility in noise by 10 to 11% in CI users. This performance improvement can be attributed to the reduction of refractory effects at the level of the auditory nerve achieved by the new sound coding strategy.

Previous studies investigated temporal response properties of the human auditory nerve through ECAP responses elicited by each single pulse of a pulse train [16–18]. ECAP responses to each pulse of a pulse train with stimulation rates up to 200 pps presented similar amplitude, however pulse trains with stimulation rates ranging between 400 to 1000 pps resulted in a maximal response for the first pulse followed by an alternating pattern of weak and strong responses. Further increase of stimulation rates above 2000 pps led to a reduction of the modulation depth in the ECAP amplitude responses. This alternating pattern can be explained by variance in absolute and relative refractory recovery times in auditory nerve fibers, leading to a non-excitable subpopulation of fibers at the time of the second pulse causing a reduced response to this pulse. Subsequently, the fibers that were not able to respond to the second pulse recover from refractory phase and contribute to a stronger ECAP amplitude response to the following stimulation pulse [18].

The present study used the clinical default stimulation rate of 900 pulses per second for each channel, a stimulation rate reported to produce refractory effects, as explained above. Moreover, it has been shown [8,19] that the ACE sound coding strategy tends to stimulate with clusters of channels in spectral regions with maximum acoustic energy (e.g. electrodes 20 to 16, 200 to 400 ms, Figure 3a). The simultaneous masking algorithm avoids clustering of stimulated electrodes by masking the neighboring channels around the channel containing the maximum energy (e.g. electrodes 19 and 17, 200 to 400 ms, Figure 3b). Simultaneous masking also leads to stimulation of electrodes outside of the main cluster (e.g. electrode 9, 200 to 400 ms, Figure 3b) leading to more sparse stimulation patterns [8,19]. Most patients reported a brighter sound when listening to these more sparse excitation patterns created by the PACE sound coding strategy [6].

The addition of a temporal masking model additionally to the simultaneous masking leads to dispersion of stimulation pulses from the channel with the maximum energy to adjacent channels. This effect becomes stronger when increasing the value of the masking time constant (Figure 3c to h) leading to a shift of stimuli away from the high energy channels towards the adjacent channels which would be completely masked in case the simultaneous masking model (PACE) had been applied alone (Figure 3 b). This effect reduces the spatial acuity of the stimulation pattern and leads to an overall reduction of the stimulation rate on the individual channels. This is a possible explanation for the better speech perception obtained with the TPACE speech coding strategy: longer duration between individual pulses gives the neural

population more time to recover from their refractory phase. This effect saturates as the best performance was achieved with a time constant $T_{1/2}$ of 0.5 ms.

It seems that the consideration of short-acting temporal masking can improve speech intelligibility in CI subjects. The median benefit of TPACE $T_{1/2} = 0.5$ ms was reliably reproduced, even though the second study had more conditions, which – likely due to the multiple comparison correction – led to non-significant differences in this second trial. Altogether, our data indicate that individual subjects perform best at different masking time constants. As we focused on temporal masking with time constants in the range corresponding with the typical absolute and relative refractory period, we anticipated that there might be a correlation between the individual recovery time of the neurons and the optimal $T_{1/2}$ value for the individual subjects.

However, the evaluation of the ECAP amplitude recovery functions did not reveal a correlation between this objective measure and the patient-specific optimal temporal masking, dashing the idea to individualize the time constants for the new strategy based on objective ECAP measures. However, a strong correlation between the benefit of TPACE and the performance with the clinically administered speech test material was found. Subjects with good test scores in the clinical aftercare obtained a larger improvement with TPACE over the ACE strategy, than patients with lower scores in the clinical routine with some of them even showing detrimental effects with TPACE. One possible mechanism that could explain this observation might be that poorer performing subjects with an impaired or degraded

auditory system are relying on some of the redundant information being discarded by the TPACE strategy. Good performers on the other hand, do benefit from the sparse stimulation of TPACE as their auditory system is still trained on normal perception from acoustic hearing with its according masking phenomena being partially mimicked in TPACE. On the other hand, this observation may be also be explained by the fact that the experiment was conducted giving very little time to the CI users to adapt to the new strategy. The generally good performing subjects may be able to adapt faster to the new strategy and gain a benefit from the temporal masking while bad performing subjects are put at a disadvantage by the acute testing scenario.

A real time implementation of the strategy on a clinical behind-the-ear speech processor can reveal if TPACE is able to improve the speech intelligibility in a more realistic setting, especially in subjects with below-average performance in a take-home evaluation with a longer adaptation period.

References

1. Loizou PC. Signal-processing techniques for cochlear implants. IEEE Eng Med Biol Mag. 1999;18(3):34–46.
2. Wouters J, McDermott HJ, Francart T. Sound coding in cochlear implants: From electric pulses to hearing. IEEE Signal Process Mag. 2015;32(2):67–80.
3. Macherey O, Carlyon RP. Cochlear implants. Curr Biol. 2014 Sep;24(18):R878–84.

- 354 4. Bierer JA. Probing the electrode-neuron interface with focused cochlear
355 implant stimulation. *Trends Amplif.* 2010 Jan;14(2):84–95.
- 356 5. Richter C-P, Rajguru S, Bendett M. Infrared neural stimulation in the cochlea.
357 In: Kollias N, Choi B, Zeng H, Kang HW, Knudsen BE, Wong BJ, et al., editors.
358 2013. p. 85651Y.
- 359 6. Büchner A, Nogueira W, Edler B, Battmer R-D, Lenarz T. Results from a
360 psychoacoustic model-based strategy for the nucleus-24 and freedom
361 cochlear implants. *Otol Neurotol.* 2008 Feb;29(2):189–92.
- 362 7. Seligman P, McDermott H. Architecture of the Spectra 22 speech processor.
363 *Ann Otol Rhinol Laryngol Suppl.* 1995 Sep;166:139–41.
- 364 8. Nogueira W, Büchner A, Lenarz T, Edler B. A Psychoacoustic “NofM”-Type
365 Speech Coding Strategy for Cochlear Implants. *EURASIP J Adv Signal Process.*
366 2005;2005(18):3044–59.
- 367 9. Büchner A, Beynon A, Szyfter W, Niemczyk K, Hoppe U, Hey M, et al. Clinical
368 evaluation of cochlear implant sound coding taking into account conjectural
369 masking functions, MP3000™. *Cochlear Implants Int.* 2011 Nov;12(4):194–
370 204.
- 371 10. Bosi M, Goldberg RE. Introduction to Digital Audio Coding and Standards
372 [Internet]. Boston, MA: Springer US; 2003.
- 373 11. Morsnowski A, Charasse B, Collet L, Killian MJ, Müller-Deile J. Measuring the
374 refractoriness of the electrically stimulated auditory nerve. *Audiol Neurotol.*
375 2006 Jan;11(6):389–402.

- 376 12. Botros A, Psarros C. Neural Response Telemetry Reconsidered : I . The
377 Relevance of ECAP Threshold Profiles and Scaled Profiles to Cochlear Implant
378 Fitting. 2010;
- 379 13. Hochmair-Desoyer I, Schulz E, Moser L, Schmidt M. The HSM sentence test as
380 a tool for evaluating the speech understanding in noise of cochlear implant
381 users. Am J Otol. 1997;18(6 Suppl):S83.
- 382 14. Quade D. Using Weighted Rankings in the Analysis of Complete Blocks with
383 Additive Block Effects. J Am Stat Assoc. 1979 Sep;74(367):680.
- 384 15. Miller CA, Abbas PJ, Brown CJ. An improved method of reducing stimulus
385 artifact in the electrically evoked whole-nerve potential. Ear Hear. 2000
386 Aug;21(4):280–90.
- 387 16. Hughes M, Castioni E, Goehring J, Baudhuin J. Temporal response properties
388 of the auditory nerve: Data from human cochlear-implant recipients. Hear
389 Res. 2012;285:46–57.
- 390 17. Hay-McCutcheon MJ, Brown CJ, Abbas PJ. An analysis of the impact of
391 auditory-nerve adaptation on behavioral measures of temporal integration in
392 cochlear implant recipients. J Acoust Soc Am. 2005;118(4):2444–57.
- 393 18. Wilson BS, Finley CC, Lawson DT, Zerbi M. Temporal representations with
394 cochlear implants. Am J Otol. 1997 Nov;18(6 Suppl):S30-4.
- 395 19. Nogueira W, Rode T, Büchner A. Spectral contrast enhancement improves
396 speech intelligibility in noise for cochlear implants. J Acoust Soc Am. 2016
397 Feb;139(2):728–39.

Subject	Age [years]	Duration of deafness at time of study [years]	Reason for deafness	Implant Type	CI usage [years]		Clinical Outcome (HSM) [%]		clinical map				
					ipsi	contra	quiet	10 dB	Tested SNR [dB]	strategy	stim. rate [pps]	# max	# el.
1.1	57	4	Sudden hearing loss	RE-24 CA	4	-	100	50	10	ACE	900	8	22
1.2	72	12	Unknown	RE-24 CA	4	10	99	31	5	MP3000	900	5	22
1.3	75	3	Morbus Meniere	RE-24 CA	3	-	100	45	5	MP3000	900	5	22
1.4	71	2	Explosion trauma	CI512	1	-	97	24	10	ACE	900	8	22
1.5	63	25	Unknown	RE-24 CA	3	20	58	NM	15	MP3000	900	5	21
1.6	32	10	Sudden hearing loss	RE-24 CA	4	10	100	58	5	ACE	1200	8	22
1.7	62	0	Sudden hearing loss	RE-24 CA	3	0,4	100	61	10	MP3000	900	5	22
1.8	70	2	Unknown	CI512	2	1	92	11	10	ACE	900	8	22
1.9	53	10	Unknown	CI512	2	1	93	0	10	ACE	900	8	22
1.10	28	1	Unknown	CI512	1	-	98	8	10	ACE	900	8	22
1.11	33	13	Unknown	RE-24 CA	4	7	100	52	5	ACE	900	8	22
1.12	64	12	Sudden hearing loss	RE-24 CA	7	4	80	20	15	ACE	500	10	20
2.1	19	8	Unknown	RE-24 CA	8	-	100	77	5	MP3000	1200	5	22
2.2	72	10	Unknown	CI512	4	5	91	15	10	ACE	900	8	22
2.3	77	12	Sudden hearing loss	CI512	4	12	85	0	15	ACE	900	8	22
2.4	53	6	Unknown	RE-24 CA	6	-	99	34	10	ACE	900	8	22
2.5	49	18	Meningitis	CI512	4	4	90	16	15	ACE	900	8	22
2.6	66	8	Sudden hearing loss	RE-24 CA	8	7	100	83	5	ACE	900	8	22
2.7	63	6	Unknown	RE-24 CA	5	4	86	8	15	ACE	900	8	22
2.8	78	1	Unknown	RE-24 CA	1	0,5	76	58	10	MP3000	900	5	22
2.9	72	18	Otitis Media	RE-24 CA	5	10	91	50	10	ACE	900	8	22
2.10	26	7	Pendred syndrome	RE-24 CA	7	-	97	8	10	MP3000	900	8	22
2.11	69	9	Sudden hearing loss	RE-24 CA	6	12	99	75	5	MP3000	900	5	22
2.12	65	11	Mumps	RE-24 CA	10	-	100	72	5	MP3000	900	6	22

Table 1. Subject demographics

399

400

401

402 **Figure 1. Block diagram illustrating the PACE strategy**

403 Adapted from [8]

Figure 2. Exponential decay of temporal masking thresholds (normalized to an amplitude of 1) at two different temporal masking half-lives $T_{1/2}$ (0.5 ms in light gray and 1.1 ms in dark grey). The stimulation rate in this example is 900 pps.

Figure 3. Stimulation patterns (electrograms) for ACE (a), PACE (b) and TPACE with different values of the half-life value $T_{1/2}$ (c-h). Current across time and electrode. Each vertical line represents the amplitude of a biphasic pulse in clinical units. The acoustic input is an audio sample containing the word “choice”.

Figure 4. A representative ECAP measurement of subject 2.2 on electrode 5. The fitted exponential function (dashed line) indicates an absolute recovery period $T_0 = 0.52 \pm 0.07$ ms, the time constant $\tau = 1.0 \pm 0.1$ ms indicates the time needed to reach 63.2 % of the maximal amplitude $A = 104 \pm 2$ μ V in this measurement.

Figure. 5. Speech intelligibility performance with different temporal masking half-life time constants using the HSM sentence test in noise. The absolute performance difference between MP3000 and different TPACE conditions is presented for the first (green) and second (blue) study. Each dot shows the averaged result of each subject in the respective condition, the group median is presented as a bar in the respective group color. Speech intelligibility in noise with TPACE $T_{1/2} = 0.5$ ms was significantly better than MP3000 in the first study ($p < 0.05$; Quade test).

Figure 6. Individual speech intelligibility results of the second study. The blue line presents the average result from two HSM sentence lists (circles) for each temporal masking half-life time constant (0.4, 0.5, 0.8 and 1.1 ms). The subjects are ordered in columns according to the temporal masking constant with the best speech intelligibility (indicated by a red arrow): patients with best results without temporal masking in the first column and patients showing best speech intelligibility with temporal masking constant $T_{1/2} = 0.8$ ms are in the fourth row. No patients showed optimal speech intelligibility with the strongest temporal masking constant of 1.1 ms.

Figure. 7. Comparison between the patient performance in the clinical setting (measured with the HSM sentence test at 10 dB SNR during the yearly control visit, Table 1) and the benefit from using TPACE with a $T_{1/2}$ of 0.5 ms. The results of the first and second study are presented in green and blue, respectively. A significant correlation between the clinical performance of the subject and the benefit from temporal masking was detected.

427

428