NRT: Comparison of Artefact Cancellation and Threshold Estimation Techniques

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Abstract

Neural response telemetry (NRT) is a process of recording electrically evoked compound action potential (ECAP) from the auditory nerve in individuals with cochlear implants. Since ECAP is a very early potential, there is an adverse effect of stimulus artefact on the recording of the ECAP via NRT. Several approaches have been proposed to reduce the stimulus artefact in NRT. A comparison of three such techniques for artefact reduction was made. Results revealed that all the techniques can be used to record NRT. A comparison of techniques available to determine the threshold NRT (T-NRT) was also done and results revealed that the visual estimation of T-NRT was a better choice.

Key words: Alternating polarity, forward masking, artefact template, visual estimation, peak picker.

Introduction

The most direct measure of auditory nerve activity in cochlear implant users is the electrically evoked compound action potential (Abbas et al., 1999). The first recording of electrically evoked whole nerve compound action potential (ECAP) from human cochlear implant users was reported by Brown, Abbas and Gantz in 1990. The method used was an adaptation of the paradigm described by Sauvage, Cazals, Erre, and Aran in1983. The term "Telemetry" describes the measurement of data and transmission of data from a remote source to a receiving station for recording and analysis (Mens, 2004). The telemetry system used to measure the ECAP in Nucleus cochlear implant users is referred to as NRT (Abbas et al., 1999). In humans this response consists primarily of a negative peak often referred to as N1 with a latency of 0.2 to 0.5 ms; and at high presentation levels, the initial negative peak is often followed by a less robust positive peak that is referred to as P2 (Brown, 2004).

While recording ECAP the problem faced is that, in addition to the neural response evoked by the electrical stimulus pulse, a very large stimulus artefact will also be recorded which is often large to saturate the recording amplifier (Brown, 2004). As a result the ECAP could not be visualized in the presence of the artefact. This problem has led to several proposals for reducing or minimizing the stimulus artefact recorded during ECAP measurement.

For recording NRT there are several techniques available in the Custom Sound EP software (version 1.3) for artefact reduction such as 1. Forward masking, 2. Artefact template, 3.

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Alternating polarity and 4. Masked response extraction. These techniques are referred to as artefact cancellation techniques in NRT. The present study is concerned with only the first three artefact cancellation techniques. Once the NRT is recorded at different current levels there is a need to identify the threshold of NRT (T-NRT), i.e., the minimum current level at which a NRT response is obtained. Threshold estimation of NRT can be done by visual detection of the NRT waveform or automatically by the software, based on some predefined rules.

The Custom Sound EP software has the option of 'peak picker' which offers the facility of automated NRT response identification. Threshold can be defined as the lowest current level, at which the peak picker identifies a NRT response. Also, there is an option for extrapolated NRT threshold identification using regression analysis. In the present study, the different artefact cancellation techniques (forward masking, artefact template and alternate polarity) and the different threshold estimation techniques (visual T-NRT estimation, peak picker based T-NRT estimation and regression analysis extrapolated T-NRT) were compared across. The different artefact cancellation and threshold estimation techniques are described briefly below.

Forward Masking

The method involves a non-simultaneous forward masking paradigm, using a masker plus probe condition, to put the auditory nerve fibers into refractory period and thereby recording only the stimulus and masker artefact. This is subtracted from the probe alone condition which consists of both stimulus artefact and neural response. The resultant is a neural response with a masker artefact. The masker artefact is then removed by recording of a masker alone condition. Once the recordings have been made in each of these three stimulation conditions, extraction of the ECAP from the stimulus artefact is accomplished in two steps. First, the average response recorded in the second condition (masker plus probe) is subtracted from the averaged response recorded in the first condition (probe alone). This subtraction yields a response in which the masker artefact has been inverted 180 degrees and the probe artefact has been minimized. The second step is to add the response recorded in the third condition (masker alone) to the product of the subtraction. This step allows elimination, or at least reduction, of the artefact associated with the masker. The main assumptions is that the masker-probe interval is short enough (<0.5 ms) for all the nerves to be in their absolute refractory state (Brown & Abbas, 1990). If the masker-probe interval is > 0.5 ms, there may be a relative refractory component at the moment of the probe stimulus in the masker-probe frame, caused by some of the nerves that have recovered from their refractory state (Klop, Hartlooper, Briare & Frijns, 2004). This will result in unwanted neural response to this probe, which influences the final response calculated.

Artefact Template

A second technique for reducing the effects of stimulus artefact is template subtraction (Miller, Abbas, Rubinstein, Robinson, Matsuoka & Woodworgh, 1998). The principle that the tissue impedance and the amplifier are linear, and a current that is twice as high will produce an artefact that is twice as large is used to record a scaled version of the artefact by measuring the artefact at a low, sub-threshold current level where there is no response and only contain artefact. The artefact template can be scaled up accordingly at a higher supra threshold stimulation level. The measured trace minus the scaled up artefact template should result in a pure neural response.

Alternating Polarity

Another common technique by which the stimulus artefact contamination can be minimized is by alternating the polarity of the stimulus in successive presentations and then averaging the response that is recorded. The artefact recorded is out of phase for the anodic-leading and cathodic-leading biphasic current stimuli. When averaging is done the out of phase stimuli artefact are averaged out. The neural response evoked by the stimulus should not reverse the polarity as the stimulus polarity is changed and therefore will be preserved in the average (Brown, 2004). Brown, Abbas and Gantz (1990) reported successful recording of NRT using alternating polarity.

Visual T-NRT estimation

In this approach a visual observation of the NRT recordings and determination of the lowest current level of the stimulus that elicits a measurable response is noted as T-NRT. This can be used either through ascending or descending approach. Ideally initial responses should be obtained at a high enough supra threshold level so that the user can be sure that the neural response decreases with amplitude. One drawback to the visual detection method is that for systems with a relatively high noise floor the true threshold can be obscured by the noise, yielding a threshold estimate that is likely to be too high (Hughes, 2006).

Peak picker based T-NRT estimation

The second option to determine T-NRT is the peak picker. The peak picker identifies the N1 and P2 of the NRT waveforms based on a set of rules that are dependent on a set of parameters such as signal to noise ratio, current level, correlation of the recording with the previous current level and correlation of the recording with a known response. These set of rules constitute the peak picker algorithm. The T-NRT can be defined as the lowest current level at which the peak picker identifies a NRT response.

Regression analysis extrapolated T-NRT

The third method of threshold estimation in NRT involves applying a regression analysis to points on an input-output (or amplitude growth) function. Threshold is determined as the level at which the regression line crosses zero amplitude (i.e., intercept of the x-axis where $y = 0$). The advantage to this method is that lower thresholds can be extrapolated for high-noise systems (Hughes, 2006).

Since there are differences in the working principle of the three different artefact cancellation techniques mentioned above it can be possible that the NRT or the ECAP recorded using them might be expected to vary in terms of latency, threshold, amplitude and morphology. Therefore the need arises to study systematically, in detail and compare the NRT recorded using the three different artefact cancellation techniques mentioned. There is a dearth of literature comparing various techniques to reduce artefact while recording NRT/ECAP.

Further comparing the threshold and the amplitude at the threshold of the recorded NRT/ECAP using different techniques to reduce stimulus artefact is also required. With respect to the threshold estimation techniques, the efficacy of the peak picker and the regression analysis in order to extrapolate threshold of NRT or T-NRT, with the NRT recorded using the three different artefact cancellation techniques needs to be studied. These methods of estimation of T-NRT need to be compared to that of obtained by the visual method of NRT estimation.

The relationship between T-NRT and behavioral thresholds have been used to program the speech processors of the cochlear implant (Brown, Hughes, Luk, Abbas, Wolaver & Gervais, 2000; Hughes, Brown, Abbas, Wolaver & Gervais, 2000; Cooper et al., 2003). If T-NRT varies with different artefact cancellation techniques the same relation cannot be used. So there is a need to study the variation, if any, in T-NRT for NRT recorded with different artefact cancellation techniques.

The objectives of the present study were:-

1. To record NRT using three different artefact cancellation techniques, viz., forward masking, artefact template and alternating polarity, on a basal, medial and apical electrode sites in the cochlea.
2. To compare the NRT recorded with the three different artefact cancellation techniques.
3. To compare the T-NRT estimated using the visual detection, peak picker and regression analysis techniques.
4. To compare the amplitude of the visually estimated T-NRT for NRT recorded with the three different artefact cancellation techniques.

Method

Following method was used to study and compare the artefact cancellation and threshold estimation techniques used in NRT. The method is explained under the following headings.

Participants

A total number of eight children (4 males and 4 females) with pre-lingual hearing loss of severe to profound degree participated in the study. The children had no contra-indication for cochlear implant surgery. All the participants were implanted with the Nucleus Freedom Contour Advanced cochlear implant systems from Cochlear Corporation, Australia. The mean age of the participants was 6.2 years (age range was from 2.6 to 13.3 years). Out of the eight participants, 7 were implanted in the right ear and one received the implant in the left ear. All the participants had a post switch-on experience of electrical hearing with the cochlear implant system for at least 3 months.

Instrumentation

Custom Sound EP (version 1.3) from Cochlear Corporation was the software that was used to record the NRT from the participants implanted with Nucleus Freedom cochlear implant systems. A laptop computer was used to run the Custom Sound EP (version 1.3) program. The programming POD, an hardware interface, established the link between the speech processor of the Nucleus Freedom cochlear implant system and the Custom Sound EP software installed in a computer. The POD was connected to the speech processor of the Freedom Cochlear implant and the other end of the programming POD was connected by a USB cable to the USB 2.0 port of the laptop.

Procedure

All the measurements were done post-operatively with 4, 12 and 20 as the probe active electrode which represented the positions in the basal, medial and apical part of the cochlea. During the recording process the participants were comfortably seated and were allowed to watch an animation film which held their attention. After the connection between the computer and the speech processor was established the advanced NRT option was selected in the Custom Sound EP (version 1.3). First an electrode impedance check was carried out in all participants to rule out any open circuit or abnormally high electrode impedances in the selected electrode pairs. NRT was then recorded, for each of the three electrodes, using three different artefact cancellation techniques. The artefact cancellation techniques were forward masking, alternating polarity and artefact template.

A test for optimized recording parameters (ORP) was carried out with each of the artefact cancellation techniques to establish the optimum gain and delay measures for recording NRT. An internal amplifier gain of 50 dB and a recording delay of 122μs were found to be optimal at all the three electrodes, for all the participants and with each of the artefact cancellation techniques. During NRT recordings the sequence of the use of the three different artefact cancellation techniques was varied to rule out any sort of order effect.

In three of the eight participants NRT could be recorded only with forward masking and alternating polarity methods of artefact cancellation as the children were awake during the testing and did not co-operate for longer testing sessions. In the rest of the five participants NRT was recorded with all the three different artefact cancellation techniques. This resulted in a total data pool of 63 T-NRT values from 24 different electrode sites.

The NRT waveforms were recorded using the protocol described in Table 1 for the three artefact cancellation techniques. Once the NRT recordings were made T-NRT values, given by the peak picker and regression analysis of the software, were recorded. In the present study the AutoNRT peak picker option was used. Peak-to-peak amplitude of visually determined N1 and P2 was recorded for the visually estimated T-NRTs. The visually estimated T-NRT taken was that which was agreed upon by a panel of three experienced audiologists so as to avoid any individual bias. This was the T-NRT estimated based on the visual observation for the purpose of the study. T-NRT was recorded:

- for each of the three recording electrodes i.e., electrode number 4, 12, and 20.
- with each of the threshold estimation techniques, for NRT recorded with the different artefact cancellation techniques.
- for each of the participant.

Table 1: Stimulating and recording parameters for NRT

Stimulation and recording parameters	Artefact cancellation techniques		
	Forward Masking	Alternating Polarity	Artefact Template
Probe indifferent electrode	MP 1	MP 1	MP 1
Probe pulse width	25 µs/phase	25 µs/phase	25 µs/phase
Probe rate	80 Hz	80 Hz	80 Hz
Probe inter phase gap	7 µs	7 µs	7 µs
Masker active electrode	Probe active electrode	NA	NA
Masker indifferent electrode	MP 1	NA	NA
Masker current level	Probe current level + 10	NA	NA
Number of maskers	1	NA	NA
Masker rate	100 Hz	NA	NA
Masker inter phase gap	7 µs	NA	NA
Masker probe interval	400 µs	NA	NA
Recording active electrode	Probe active electrode + 2	Probe active electrode + 2	Probe active electrode + 2
Recording indifferent electrode	MP 2	MP 2	MP 2
Recording Gain and Delay	Based on ORP	Based on ORP	Based on ORP
Number of sweeps	50	50	50
Measurement window	1600 µs	1600 µs	1600 µs
Effective sample rate	20 kHz	20 kHz	20 kHz
Artefact template current level	NA	NA	Probe current level – 15
Scaling factor	NA	NA	Auto
No. of sweeps for template	NA	NA	500

Note: NA = Not applicable. MP1, MP2: Monopolar stimulation modes

The artefact cancellation techniques were statistically compared under the following stages:

Stage I: Comparison across different artefact cancellation techniques based on visually estimated T-NRT at each of the three electrodes.

Stage II: Comparison across different artefact cancellation techniques based on peak picker estimated T-NRT at each of the three electrodes.

Stage III: Comparison across different artefact cancellation techniques based on regression analysis estimated T-NRT at each of the three electrodes.

Stage IV: Comparison across different artefact cancellation techniques based on the amplitude of the visually estimated T-NRT at each of the three electrodes.

The methods of threshold estimation were statistically compared under the following stages:

Stage V: Comparison across different methods of threshold estimation for NRT recorded with forward masking at each electrode.

Stage VI: Comparison across different methods of threshold estimation for NRT recorded with artefact template at each electrode.

Stage VII: Comparison across different methods of threshold estimation for NRT recorded with alternating polarity at each electrode.

Results & Discusson

For statistical comparison Friedman's test of significance was carried out across the artefact cancellation techniques and threshold estimation methods in the all the seven stages described earlier. Upon the presence of any significant statistical difference, Wilcoxon signed rank test was carried out to find out which of the artefact cancellation techniques or threshold estimation methods had significant difference. The results for seven different stages of comparison are discussed below.

Stage I

The comparison across the artefact cancellation techniques based on the visually estimated T-NRT in each of the electrodes revealed that there was no significant difference, even at 0.05 level of significance in any of the electrodes. Table 2 shows mean and standard deviation values for visually estimated T-NRT values with forward masking, alternating polarity and artefact template on the 4th, 12th and 20th electrodes.

Table 2: Mean and standard deviation (SD) values of visually estimated T-NRT for different electrodes, using different artefact cancellation techniques

Recording Electrode	Artefact Cancellation Techniques	Mean	Standard Deviation
Electrode 4	Forward Masking	178.88	4.73
	Alternating Polarity	181.63	4.21
	Artefact Template	180.60	7.70
Electrode 12	Forward Masking	179.75	14.37
	Alternating Polarity	182.38	14.79
	Artefact Template	184.00	13.00
Electrode 20	Forward Masking	164.00	14.37
	Alternating Polarity	172.13	14.79
	Artefact Template	171.80	13.00

Although there was no significant difference seen comparison of the mean threshold revealed that the mean threshold of the visually detected T-NRT was lowest for NRT recorded with forward masking paradigm (Table 2 and Figure 1). In the forward masking paradigm the stimulus artefact is recorded separately in the absence of any stimulus response as the nerve fibers are put to refractory period. The stimulus artefact present in the probe alone condition and probe-plus-masker condition is expected to be similar as in both cases the probe level is same. Since the stimulus artefact is measured with precision it can be expected to be cancelled out and the true neural response be recorded.

In the alternating polarity method of artefact cancellation it is not always true that the neural response is identical in response to either anodic-leading or cathodic-leading biphasic current pulses (Van Den Honert & Stypulkowski, 1987; Miller, Abbas, Rubinstein, Robinson, Matsuoka & Woodworgh, 1998; Miller, Robinson, Rubinstein & Matsuoka, 1999). Klop, Hartlooper, Briare and Frijns in 2004 reported that the N1 and P2 latencies are shorter for cathodic-first (0.13 and 0.32 ms, respectively) than for anodic-first stimuli (0.16 and 0.38 ms, respectively). As the N1-P2 peaks vary for anodic-leading and cathodic-leading biphasic current pulses it may affect the averaged response and thereby the threshold.

In the artefact template technique the scaled down template of the artefact is always measured at a lower probe level than the probe level used for measuring the NRT. The artefact template is then scaled up accordingly when a recording is done at threshold level. The principal limitation to this method, as reported by Brown (2004), is that the amplifier and tissue conductance should be perfectly linear to produce exactly the same shaped artefact at a lower current level which is generally not the case. As a result the scaled up template of the artefact can be either overestimating or underestimating the actual artefact at certain probe level. In either case it will distort the ECAP to a certain extent and hence might be expected to overestimate the NRT threshold. It also requires a system with very low levels of ambient noise.

Stage II

The comparison across the different artefact cancellation techniques based on the peak picker estimated T-NRT in each of the electrodes revealed that there was a significant difference between forward masking and alternating polarity techniques for the 4th electrode ($p<0.05$) and 20th electrode ($p<0.05$). Table 3 shows mean and standard deviation (SD) values of T-NRT estimated by peak picker, using the three different artefact cancellation techniques, for the 4th, 12th, and 20th electrode. The mean T-NRT was lowest with the forward masking technique in all the three electrodes.

It is to be remembered that there are two peak picker options. One is the AutoNRT peak picker and the other one is the standard peak picker. In the present study the AutoNRT peak picker was used because it was expected that the standard peak picker which can be user defined will have good correlation with the visually estimated T-NRT.

Table 3: Mean and standard deviation (SD) values of peak picker estimated T-NRT for different electrodes using different artefact cancellation techniques

Recording Electrode	Artefact Cancellation Techniques	Mean	Standard Deviation
Electrode 4	Forward Masking	171.75	6.02
	Alternating Polarity	181.00	4.04
	Artefact Template	176.60	9.32
Electrode 12	Forward Masking	176.25	15.66
	Alternating Polarity	181.00	14.52
	Artefact Template	182.20	13.66
Electrode 20	Forward Masking	161.50	18.37
	Alternating Polarity	172.00	23.60
	Artefact Template	168.60	12.66

The significant difference seen between forward masking and alternating polarity based on peak picker estimated T-NRT is because of the fact that with the alternating polarity the peak picker was identifying NRT tracings as response at a higher stimulation level that were very near to actual T-NRT. Whereas with forward masking peak picker was identifying many NRT tracings as response at very lower stimulation levels which were not NRT response as there were no visible ECAP. The peak picker estimated T-NRT responses with artefact template were generally near to that picked with the alternating polarity or in between that of the T-NRT recorded with forward masking and alternating polarity. The mean T-NRT based on peak picker was always lowest for NRT recorded with the forward masking paradigm, in all the electrodes, as it detected many tracings as NRT responses at sub-threshold levels where no visible ECAP were present.

Stage III

In this stage comparison across the artefact cancellation techniques based on the regression analysis estimated T-NRT was made in each of the electrodes. Table 4 shows mean and standard deviation (SD) value for T-NRT estimated by regression analysis using three different artefact cancellation techniques on three different electrodes.

Table 4: Mean and standard deviation (SD) values T-NRT estimated from regression analysis for different electrodes using different artefact cancellation techniques

Recording Electrode	Artefact Cancellation Techniques	Mean	SD
Electrode 4	Forward Masking	170.82	6.29
	Alternating Polarity	180.98	4.00
	Artefact Template	177.06	9.13
Electrode 12	Forward Masking	174.15	14.30
	Alternating Polarity	180.07	12.97
	Artefact Template	180.65	13.40
Electrode 20	Forward Masking	160.13	19.41
	Alternating Polarity	167.58	21.83
	Artefact Template	164.57	13.07

The comparison across the artefact cancellation techniques based on the T-NRT estimated by regression analysis in each of the electrodes revealed that there was a significant difference ($p<0.05$) between forward masking and alternating polarity, based on the T-NRT established by regression analysis on the 4th electrode. Though the mean differences were not significant at the other electrodes with other artefact cancellation techniques, the T-NRT estimated with regression analysis were again the lowest with the forward masking technique for all the electrodes.

The extrapolated T-NRT given by linear regression analysis is based on the correct responses identified by the NRT software at different stimulation levels and involves applying a regression analysis to points on an input-output (or amplitude growth) function. Threshold is determined as the level at which the regression line crosses zero amplitude (i.e., intercept of the x-axis where $y = 0$). The T-NRT based on regression analysis can be affected if the peak picker marks the amplitude measures in NRT tracings where there are actually no responses. Similar finding was reported by Hughes (2006) wherein when the amplitude measures were unmarked on the no-response waveforms, the linear regression based T-NRT became virtually the same as the visual detection threshold. Since peak piker identification of correct NRT responses with alternating polarity and forward masking different a significant difference, at times, can be expected in the regression analysis based estimations for T-NRT recorded with these two methods.

The regression analysis estimated T-NRT is also based on the amplitude growth function linearity assumption. Typically the amplitude growth function is linear at higher current levels and tails off near threshold but also flattens out at very high current levels, giving an over all sigmoidal function (Botros, Dijk & Killian, 2006). These authors also reported that non-linearity near threshold poses a difficulty for automated systems that are based on extrapolated threshold method.

Stage IV

Comparison of the amplitude of the visually estimated T-NRT waveform recorded using the three different artefact cancellation techniques revealed that there was a significant difference between the amplitude of the T-NRT recorded with the three different artefact cancellation techniques($p<0.05$). Further analysis revealed significant differences between visually established T-NRT amplitude recorded with alternating polarity and forward masking and between visually estimated T-NRT amplitude recorded with artefact template and alternating polarity for each the 4th, 12th and 20th electrode($p<0.05$). The amplitude of the N1 and P2 peaks in the T-NRT tracings were recorded and the peak to peak amplitude between the N1-P2 complex was taken as the amplitude of the T-NRT. Table 5 shows mean and standard deviation (SD) values of the amplitude (μV) of the visually estimated T-NRT recorded with the three different artefact cancellation techniques on electrode number 4, 12 and 20. The lower mean amplitude of visually estimated T-NRT recorded with alternating polarity as compared the mean amplitude of the visually estimated T-NRT recorded with other two artefact cancellation techniques can be observed in Figure 4. From Figure 4, it is noted that the NRT amplitude did not vary much across the electrodes with alternating polarity technique. The amplitude of NRT was always least with alternating polarity compared to artefact template and forward masking, in all the electrodes. This is evident from the mean amplitude of the T-NRT recorded with alternating polarity, which was always least for alternating polarity in all the electrodes. The amplitude was highest for forward masking in the 4th and 20th electrode and, for artefact template in 12th electrode.

Table 5: Mean amplitude of the visually estimated T-NRT for different artefact cancellation techniques on different electrodes

Recording Electrode	Artefact Cancellation Techniques	Mean	SD
Electrode 4	Forward Masking	17.67	6.88
	Alternating Polarity	7.24	2.40
	Artefact Template	12.39	1.23
Electrode 12	Forward Masking	14.51	1.05
	Alternating Polarity	7.33	2.38
	Artefact Template	16.70	16.70
Electrode 20	Forward Masking	16.57	1.66
	Alternating Polarity	7.30	1.94
	Artefact Template	15.03	4.86

The lower amplitude for NRT recorded with alternating polarity can be attributed to the fact that it is not always true that the neural response is identical in response to either anodic-leading or cathodic-leading biphasic current pulses as reported by Van Den Honert and Stypulkowski, (1987); Miller, Abbas, Rubinstein, Robinson, Matsuoka and Woodworgh, (1998); Miller, Robinson, Rubinstein and Matsuoka, (1999). Klop, Hartlooper, Briare, and Frijns, (2004) reported that the N1 and P2 latencies are shorter for cathodic-leading (0.13 and 0.32 ms respectively) than for anodic-leading stimuli (0.16 and 0.38 ms respectively). Since the N1 and P2 is recorded at different latencies with anodic-leading and cathodic-leading biphasic current pulses they will lie at different sampling points during recording for half of the anodic-leading biphasic current pulse stimuli and half of the cathodic-leading biphasic current pulse stimuli. This will lead to lesser N1-P2 peak-to-peak amplitude recorded after averaging, when compared to the averaged N1-P2 peak-to-peak amplitude of any other method where the N1 and P2 latencies fall at similar latencies and hence at similar sampling points for each stimulation. The findings of this study is consistent with that of Hughes, Abbas, Brown, Behrens and Dunn (2003), who reported that the amplitude of the NRT recorded with alternating polarity method tends to be significantly smaller than that obtained with the subtraction method ($r = 0.97$, $p < 0.0001$) yielding higher thresholds with alternating polarity ($r = 0.86$, $p = 0.01$).

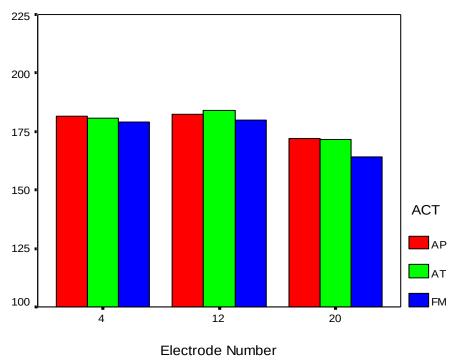

Fig. 1: Bar diagram of the mean T-NRT estimated visually with the different artefact cancellation techniques

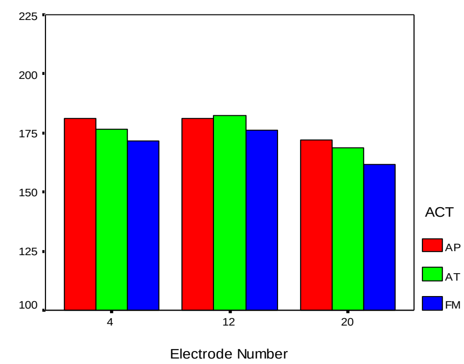

Fig. 2: Bar diagram of the mean T-NRT estimated with peak picker for different artefact cancellation techniques

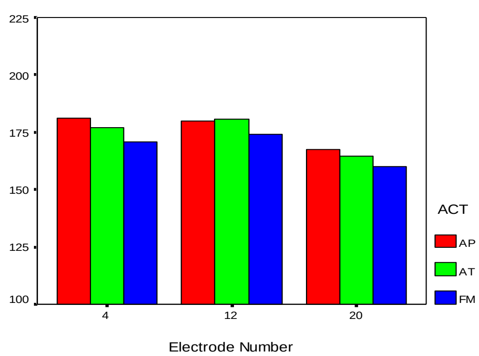

Fig. 3: Bar diagram of mean T-NRT estimated by regression analysis for different artefact Cancellation techniques.

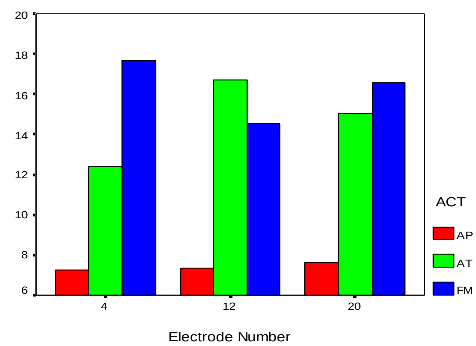

Fig. 4: Bar diagram of the mean of visually estimated T-NRT with different artefact cancellation techniques

Note: ACT = artefact cancellation techniques; AP = alternating polarity; AT = artefact template; FM= forward masking

Stage V

The visual, peak picker and regression analysis estimated T-NRT for NRT recorded with forward masking were compared at each of the 4th, 12th, and 20th electrode. Statistical comparison revealed that when forward masking was used as an artefact cancellation technique, there were significant differences between the different methods of estimating T-NRT ($p<0.05$). Further analysis revealed that when forward masking was used significant difference was seen between T-NRTs that were visually estimated and T-NRTs that were estimated using the regression analysis and the peak picker methods ($p<0.05$). No statistical difference was observed even at 0.05 level of significance between the peak picker estimated and regression analysis estimated T-NRTs. Similar findings were observed in all the electrodes.

There was no significant difference between peak picker estimated and regression analysis estimated T-NRT, when forward masking was used, because of the fact that the regression based extrapolated threshold considers the responses picked up by the peak picker and involves applying a regression analysis to points on an input-output (or amplitude growth) function. The same trend was observed in every case and no significant difference between peak picker and regression analysis estimated T-NRT was seen in any electrode with any artefact cancellation technique.

A significant difference between visual and peak picker based T-NRT for NRT/ECAP recorded with forward masking as artefact cancellation technique was seen because of the fact that the peak picker identified NRT tracings as responses even where no visible ECAP existed. The present finding which show that peak picker identified NRT tracings with no visible ECAP as responses is consistent with the findings of Hughes (2006).

Figure 5 depicts that when NRT waveforms recorded with forward masking as the artefact cancellation technique the peak picker identified an NRT response at current levels where no visible ECAP can be observed. The actual visually detected threshold was at 183 current levels. Also in Figure 5 we can see the improper marking of the P2 latency even when the NRT tracing is correctly identified as a response. For example, the P2 latency was picked too late by the peak picker for NRT tracing with 186 current levels. Also, P2 is expected to reduce in latency with increase in stimulus level. However, the P2 latency picked for NRT tracing with 183 current levels is less than the P2 latency picked for NRT tracing with 190 current levels.

As discussed earlier the regression analysis based estimation of T-NRT involves applying a regression analysis to points on an input-output (or amplitude growth) to the responses picked by the peak, so an incorrect marking of responses by the peak picker will also affect the regression based T-NRT. This is why a significant difference was seen between visual and regression based T-NRT with forward masking as artefact cancellation technique for recording NRT. Similar results of incorrect NRT response identification by peak picker affecting the regression T-NRT was reported by Hughes (2006).

Stage VI

Similar to NRT recorded with forward masking NRT recorded with artefact template also had significant differences between the estimated T-NRT based on visual detection and peak picker and between the estimated T-NRT based on visual detection and regression analysis. The findings can be discussed on similar lines as above. The peak picker picked up incorrect NRT tracings as responses for NRT recorded with artefact template as artefact cancellation technique, even when there was no visible ECAP. This is understood in Figure 6 where NRT tracings at 161 and 164 current levels have been picked as NRT responses. The incorrect placing of cursors of N1 and P2 peaks can also be observed.

Stage VII

Comparison of the visual, peak picker and regression estimated T-NRT for NRT recorded with alternating polarity as artefact cancellation technique did not show any significant difference in any of the electrodes. The reason can be attributed to the ability of the peak picker to identify NRT responses correctly when NRT was recorded with alternating polarity as artefact cancellation technique. This is understood from Figure 7. It is to be noted that visually NRT with 175 current levels was taken as the T-NRT and the peak picker picked up 174 current levels as the T-NRT.

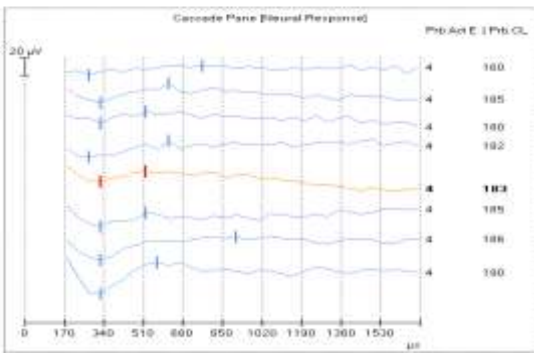

Fig. 5: Peak picker marked NRT waveforms recorded with forward masking at different current levels

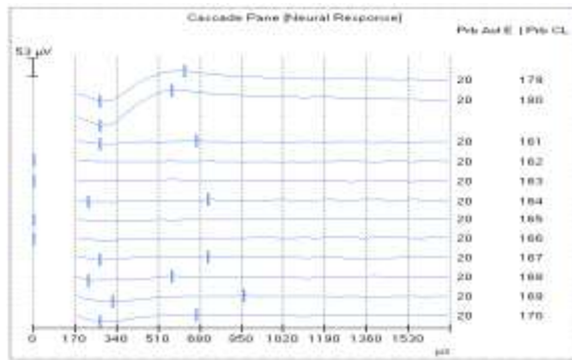

Fig. 6: Peak picker marked NRT waveforms recorded with artefact template at different current levels

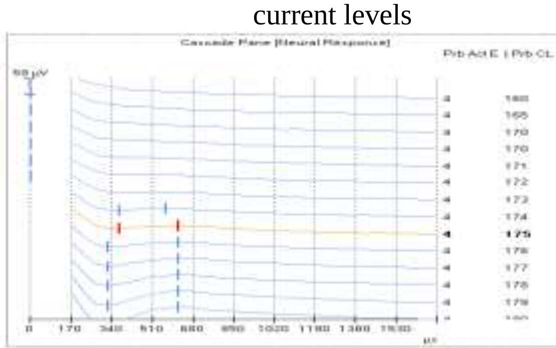

Fig. 7: Peak picker marked NRT waveforms recorded with alternating polarity at different current levels

Conclusion

The present study shows that all the three artefact cancellation techniques might be used with confidence for recording NRTs for clinical purpose. A visual estimation T-NRT if used will not result in significant differences in T-NRT. However, amplitude of NRT recorded with alternating polarity will be consistent as compared to the other two artefact cancellation techniques. The use of the peak picker and regression analysis techniques for determining T-NRT should be done with caution. Discarding incorrectly identified peak picker responses will improve the efficacy of the regression analysis T-NRT.

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