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Title: Reducing blanking artifact in electrically evoked compound action potentials

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Abstract: The main source of distortion in the recording of the electrically evoked compound action potentials is the stimulus artifact. The popular hardware blanking technique tends to reduce this artifact, but generates a blanking artifact as a consequence of the transient state in the amplifier. In this paper we propose two techniques to deal with the blanking artifact. The proposed techniques are combined with conventional and generalized alternating stimulation in order to reduce both stimulus and blanking artifacts in the recording of the evoked potentials. A comparison over 126 evoked potential recordings reveals that the proposed blanking artifact reduction methods improve the quality of electrically evoked compound action potential recordings.

Keywords: Electrically Evoked Compound Action Potential, ECAP, blanking artifact, stimulus artifact, cochlear implant.

1. Introduction

Nowadays, the electrically evoked compound action potentials (ECAPs) are widely used in clinical and research applications, since they provide an assessment of auditory nerve status [1] and may assist the clinician in fitting the cochlear implant speech processor [2-6]. These measurements represent the compound action potential associated with the synchronous firing of the neurons in the spiral ganglion evoked by electrical stimulation. The typical neural response waveform is characterized by a negative peak N1 (with a latency of 200-400µs) followed by a positive peak P2 (with a latency of 500-700µs).

Most modern cochlear implant systems allow ECAPs to be recorded [7] [8] [9] [10]. The recording system integrated into the implantable device includes the amplification of the input signal, analog to digital conversion, encoding, storage and data transfer to an external system, where recorded data can be processed [7] [8] [9]. After injection of current pulses in an intra-cochlear electrode the ECAP can be recorded with an intra-cochlear recording electrode positioned close to the stimulation electrode. In addition to the compound action potential, recordings also contain artifact coming from different sources. Two different kinds of artifacts can be considered: random artifacts and synchronized artifacts. The random artifacts have various possible origins, such as neural or muscular activity of the subject, external electrical interference or internal noise in the acquisition sub-system. Since these artifacts are not synchronous with the stimulation pulses, they can be effectively reduced with the well-known ensemble averaging method, by averaging a number of responses [11]. In contract, the synchronized artifacts (such as the stimulus artifact, the blanking artifact or for instance a synchronous noise induced by the stimulation circuit) are coherent with the stimulation pulses and cannot therefore be removed by the ensemble averaging technique.

The stimulus artifact is the main source of distortion in ECAP recording. This artifact, caused by the stimulus applied to evoke the response, consists of a peak followed by an exponential decay [12] [13]. The stimulation pulses require voltages typically in the range of 1-5V and the smallest ECAP value that can reliably be measured has an amplitude of about 100μV [14]. The stimulus artifact cannot be removed by the conventional technique of ensemble averaging since it is synchronous with the stimulation pulse [15]. In addition, stimulus artifact overlaps the evoked response in both the time and frequency domains, such that conventional time windowing and frequency filtering are incapable of removing stimulus artifact without distorting the evoked response. The most commonly used methods to reduce stimulus artifact in ECAP recording are based on combining the responses to different types of stimulation pulses, such as alternating stimulation [14] [16], masker-probe paradigm [17] [18] [19] or triphasic stimulation [20] [21] [22].

In addition to these methods, a very often used technique for stimulus artifact suppression is hardware blanking [23] [24]. With this technique the input of the amplifier is in short-circuit during the stimulation pulse. The major disadvantage of the hardware blanking technique is that the blanking time interval is usually a fixed value. This may lead to clipping or blanking out the evoked response if the blanking time interval is set too long or if the stimulation parameters (for instance, width of the stimulation pulse) change [25]. This is especially true in ECAP recording, since the stimulus and recording sites are close together and the stimulus artifact interfere with the evoked response. The approach also fails to take into account the dynamic effect of stimulation whereby the tail of the stimulus artifact may survive the blanking interval (if set too short) and be recorded along with the evoked response [25]. Additionally, though the blanking hardware technique tends to reduce the stimulus artifact, the transient state of the amplifier introduces a new artifact, referred to as blanking artifact. In this work we propose two techniques to deal with the remaining blanking artifact. The proposed techniques combined with stimulus artifact reduction methods tend to reduce both artifacts in the recording of ECAPs.

2. Material and Methods

2.1. ECAP Acquisition

Fifty subjects (aged from 6 months to 74 years) participated in this study. All of them were implanted with the Med-El Pulsar CI^{100} cochlear implant [10] [13] [26]. Each prospective subject was given an informed-consent form explaining the purpose and procedures involved in the study. If the patient agreed to participate, the form was signed and the subject was provided with a copy. The experimental protocol was approved by the Ethic Committee of San Cecilio University Hospital, Granada (Spain).

The ECAP recording system integrated in the Pulsar CI^{100} cochlear implant allows different configurations to be used for stimulation and recording. The stimulation configuration used in this study was set up in alternating mode.

Figure 1 shows the S_{ac} and S_{ca} stimulation patterns corresponding to this mode. S_{ac} and S_{ca} stimulation patterns use anodic-cathodic (ac) and cathodic-anodic (ca) biphasic pulses as stimulation, respectively. Biphasic pulses were set up with durations of each phase between 30 and 45μs, and amplitudes under 1200μA. The stimulation level is defined as the product of the duration (in μs) of each phase of the biphasic pulse and the amplitude (in μA) of the stimulation pulses and it is expressed in charge units (nanoCoulomb, nC). The recording of the ECAPs begins to be measured after a blanking time interval of 125μs. In order to obtain each recording, we averaged 50 responses for each stimulation pattern by the conventional ensemble-averaging method. The stimulation rate used was 50Hz (a response was recorded every 20ms). If the stimulation level used is high enough to elicit an evoked response, the recordings corresponding to the S_{ac} and S_{ca} stimulation patterns can be defined as:

$$R_{ac} \approx A_s + A_b + B \tag{1}$$

$$R_{ca} \approx - A_s + A_b + B \tag{2}$$

where A_s and A_b are the stimulus and blanking artifacts, respectively, and B is the biological response. If R_{ac} and R_{ca} recordings are acquired with a null stimulation level neither stimulus artifact nor biological response will be measured and these recordings therefore will only contain the blanking artifact. In this paper we propose to use the R_{ac} recording acquired with a null stimulation level as a blanking artifact template:

$$R_{blank} = R_{ac}(0nC) \approx A_b \tag{3}$$

Assuming the linearity of the system and a fully symmetrical amplifier, we have acquired the ECAPs using the stimulus artifact reduction method of conventional alternating stimulation. This method provides a response that is obtained as the average of recordings using anodic-cathodic and cathodic-anodic biphasic pulses as stimulation [14]. Using the stimulation patterns involved in this study, the conventional alternating recording (R_{alt}) can be obtained as:

$$R_{alt} = 1/2 \cdot R_{ac} + 1/2 \cdot R_{ca} = B + A_b \tag{4}$$

Under this approach, the blanking artifact is not suppressed. In addition, the biological response is assumed to be independent of the polarity of the first phase of the stimulation pulse (i.e. similar for anodic-cathodic and cathodic-anodic stimuli), though other authors have demonstrated that the neural responses to each stimulus polarity are not necessarily equal in amplitude or latency [19] and that the auditory nerve has polarity-dependent sensitivity and responds with polarity-dependent latency in cats and guinea pigs [26]. On the other hand, the stimulus artifacts are assumed to change their polarities when anodic-cathodic or cathodic-anodic biphasic stimulation pulses are used. However, this assumption is hardly ever met. Figure 2 shows instances of R_{ac} and R_{ca} recordings acquired for two different patients increasing the stimulation level. The difference between these two recordings is also shown. The R_{ac} and R_{ca} recordings acquired with the highest stimulation level, that is, 12nC (up) and 26nC (down) contain the biological response plus both blanking and stimulus artifacts (equations (1) and (2)). Since the stimulation level used are not high enough to elicit an evoked response, the R_{ac} and R_{ca} recordings acquired with a stimulation levels of 4nC and 8nC (up) and of 9nC and 17nC (down) only contain both blanking and stimulus artifacts (equations (1) and (2)). We can observe that the artifacts are not equal when anodic-cathodic or cathodic-anodic biphasic stimulation pulses are used and that the stimulus artifacts and presumably the blanking artifacts increase in amplitude with the stimulation level. The R_{ac} and R_{ca} recordings acquired with a null stimulation level only contain the blanking artifact (equations (1) and (2)). We can observe that the blanking artifacts are similar for both R_{ac} and R_{ca} recordings.

We have also acquired ECAPs using generalized alternating stimulation in order to deal with the limitations associated with the conventional method. This stimulus artifact reduction method has been described in a previous paper [16]. Instead of using similar weights, 0.5 for anodic-cathodic and 0.5 for cathodic-anodic stimulation pulses, they are combined using different weights: α and $(1 - \alpha)$ for anodic-cathodic and cathodic-anodic stimulation pulses, respectively. The generalized alternating recording (R_{galt}) can be obtained as:

$$R_{galt} = \alpha \cdot R_{ac} + (1 - \alpha) \cdot R_{ca} \qquad (5)$$

In order to calculate the α weight, we propose the use of an expert-based automatic method that assesses the quality of an ECAP response (Q), as described in a previous paper [16]. This method assesses the quality of an ECAP in the range of 0-10. Instances of registers with different quality values assigned by a human expert (Q_E) are shown in figure 3. Due to the exponential behavior of the stimulus artifact [12] [13], an ECAP recording is considered to be ideal if (1) the waves N1 and P2 can easily be identified, (2) the amplitude, quantified as the difference between both peaks, can reliably be measured and

(3) it presents flat behavior after the evoked potential [16]. Thus, the optimal value of the weight is automatically calculated as that one that maximizes the quality of the generalized alternating recording (equation (5)) and therefore that one that minimizes the stimulus artifact. Note that the conventional alternating stimulation is a particular case of the generalized alternating stimulation with $\alpha=0.5$. The optimal weight was explored within an interval of ±0.5 around the conventional value (i.e. $\alpha \in [0,1]$).

2.2. Blanking artifact reduction methods

This paper proposes to combine the stimulus artifact reduction methods described above with two proposed blanking artifact reduction techniques:

- Conventional blanking artifact reduction method. Since R_{blank} represents an estimation of the blanking artifact (equation (3)), we propose to subtract this template with a weight equal to -1 to conventional and generalized alternating recordings (equations (4) and (5), respectively):

  $$R_{alt+b} = R_{alt} - R_{blank} \tag{6}$$

  $$R_{galt+b} = R_{galt} - R_{blank} \tag{7}$$

- Generalized blanking artifact reduction method. Nonlinearities due to the electrode-tissue interface, the recording system, etc. [27] [28] make a fixed weight of -1 suboptimal for blanking artifact reduction. In addition, the blanking artifact presumably increases in amplitude with the stimulation level and R_{blank} represents a blanking artifact template acquired with a null stimulation level. Thus, we extend the concept of conventional blanking artifact reduction method by subtracting the blanking artifact template (equation (3)) with an optimal weight (β) to conventional and generalized alternating recordings (equations (4) and (5), respectively):

$$R_{alt+gb} = R_{alt} + \beta \cdot R_{blank} \quad (8)$$

$$R_{galt+gb} = R_{galt} + \beta \cdot R_{blank} \quad (9)$$

The optimal β weight is automatically calculated using the expert-based automatic method [16] as that one that maximizes the quality of the evoked response and therefore that one that minimizes the blanking artifact. The optimal value of β weight is selected in the interval [-1.5,0.5]. Note that the blanking artifact template cannot be used (β=0) and that the conventional blanking artifact reduction technique is a particular case of the generalized blanking artifact reduction with β=-1.

In the experiments performed in this study, the optimal α and β values were automatically calculated using a MATLAB two-stage implementation running on a laptop computer with an Intel Core Duo CPU at 1.86 GHz. The first stage calculates the quasi-optimal values with a step of 0.05 in the interval of width 1 (i.e. $\alpha \in [0,1]$) or width 2 (i.e. $\beta \in [-1.5,0.5]$). The second stage then calculates the optimal α and β values with a step of 0.005 in the interval of width 0.1 centered at the quasi-optimal values.

In order to analyze the statistical significance of the improvement achieved by the proposed blanking artifact reduction techniques with respect to apply only stimulus artifact reduction methods, Wilcoxon rank sum test [29] was applied over a set of 126 ECAP recordings with an identifiable evoked response. We considered a statistically significant improvement if the p-value (probability that the observed improvement occurred by pure chance) was smaller than 0.01.

3. Results

Figure 4 shows instances of recordings associated with conventional and generalized alternating stimulation (R_{alt} and R_{galt}, respectively). Recordings using anodic-cathodic and cathodic-anodic biphasic pulses as stimulation (R_{ac} and R_{ca}, respectively) and the blanking template (R_{blank}) used in the proposed conventional (+b) and generalized (+gb) blanking artifact reduction methods are shown. The values of the α and β weights provided by the automatic method are also shown. We can observe that the proposed generalized blanking technique always provides better quality than recording the evoked potential with only the stimulus artifact reduction method (i.e. a more consistent identification of waves N1 and P2 and a flatter behavior after wave P2). However, the proposed conventional blanking technique may deteriorate the evoked potential since the blanking template is subtracted with a fixed weight (see recording R_{alt+b} in bottom panel of figure 4). Figure 5 shows four ECAPs acquired with conventional and generalized alternating stimulation. These stimulus artifact reduction methods are combined with the proposed blanking artifact reduction techniques. The automatically estimated quality (Q) of each method is also indicated. We can observe that using the conventional blanking artifact reduction method may provide evoked potentials of worse quality. However, the quality improvement of the generalized blanking technique is assured by the method, since the optimal value of β weight is selected with a quality criterion and non-using blanking artifact reduction is a particular case of generalized blanking artifact reduction method with β=0.

Table 1 shows the mean and standard deviation of the automatically estimated quality for 126 ECAP recordings. Mean and standard deviation of α and β weights are also shown. The relatively high standard deviation of the optimal weights shows that the specific optimization for each ECAP recording is important for artifact reduction. The quality improvements achieved with the proposed blanking artifact reduction techniques are statistically significant (all tests showed highly significant differences at $p<0.01$). Improvements with the generalized technique with respect to the conventional blanking artifact reduction technique are also statistically significant ($p<0.01$ in both conventional and generalized alternating stimulation).

Although generalized techniques, in both stimulus and blanking artifact reduction methods, provide higher average quality than conventional techniques, the time increment associated with the computation of the optimal weights should be taken into account. Table 1 also shows the acquisition time (in seconds) of the recordings involved in each artifact reduction method and the computational load (in seconds) associated with the calculation of the optimal weights.

4. Discussion

This paper proposes the use of an expert-based automatic method [16] to reduce both stimulus and blanking artifacts in ECAP recording. Conventional alternating stimulation is one of the most used method to reduce stimulus artifact. This method combines anodic-cathodic and cathodic-anodic biphasic pulses with a fixed weight of 0.5. Since non-linearities due to the electrode–tissue interface, the recording system, etc. [27] [28] make 0.5 sub-optimal for artifact reduction, the evoked potential has also been acquired using generalized alternating stimulation [16]. In this technique, the recordings acquired with bipolar stimulation (anodic/cathodic and cathodic/anodic) are combined according to a weight α, which is automatically calculated according to an expert-based criterion. Thus, generalized alternating stimulation overcomes the limitations of the conventional method, but the blanking artifact remains in the recording. In order to deal with this artifact, two methods are proposed in this paper: conventional (equations 6 and 7) and generalized (equations 8 and 9) blanking artifact reduction methods. The conventional method subtracts a blanking artifact template with a fixed weight equal to -1 to conventional and generalized alternating recordings, meanwhile the generalized method subtracts the template with an optimal weight (β), which is automatically calculated using an expert-based automatic method [16].

The proposed methods have been analyzed over a set of 126 ECAP recordings with an identifiable evoked response. However, since the automatic computation of α and β weights is based on an expert criterion, the possibility of obtaining a false ECAP using the generalized methods should be considered, especially if these methods want to be used in an automatic ECAP detection system. In addition, the proposed methods do not facilitate an human expert to detect ECAP responses acquired with a stimulation level close to the threshold, but may assist in an automatic system since both stimulus and blanking artifacts are reduced.

According to our results, although the conventional proposed blanking technique provides a better average quality than recording the ECAPs using only the stimulus artifact reduction methods, its use may distort the evoked potential since the blanking artifact template is subtracted with a fixed weight. However, the proposed generalized blanking artifact reduction technique always allows to reduce the blanking artifact and therefore improve the quality of the recordings. Combining this generalized blanking technique with the stimulus artifact reduction methods provides the highest average quality with a reasonable time increment.

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REFERENCES

[1] C.A. Miller, P.J. Abbas, P.K. Robinson, The use of long-duration current pulses to assess nerve survival, Hearing Res. 78 (1994) 11-26.

[2] C.J. Brown, Clinical uses of electrically evoked auditory nerve and brainstem responses, Otolaryng Head Neck. 11 (2003) 383-387.

[3] K.H. Franck, S.J. Norton, Estimation of Psychophysical Levels Using the Electrically Evoked Compound Action Potential Measured with the Neural Response Telemetry Capabilities of Cochlear Corporation's CI24M Device, Ear Hearing. 22 (2001) 289-299.

[4] M.L. Hughes, C.J. Brown, P.J. Abbas, Comparison of EAP Thresholds with MAP Levels in the Nucleus 24 Cochlear Implant: Data from Children, Ear Hearing. 21 (2000) 164-174.

[5] M. Polak, A. Hodges, T. Balkany, ECAP, ESR and subjective levels for two different Nucleus 24 electrode arrays, Otol Neurotol. 26 (2005) 639-645.

[6] G.F. Smoorenburg, C. Willeboer, J.E. Dijk, Speech perception in Nucleus CI24M cochlear implant users with processor settings based on electrically evoked compound action potential thresholds, Audiol Neuro-otol. 7 (2002) 335-347.

[7] C.J. Brown, P.J. Abbas, B. Gantz, Preliminary experience with neural response telemetry in the nucleus CI24M cochlear implant, Am J Otol. 19 (1998) 320-327.

[8] N. Dillier, W.K. Lai, B. Almqvist, Measurement of the electrically evoked compound action potential via a neural response telemetry system, Ann Oto Rhinol Laryn. 111 (2002) 407-414.

[9] J.H. Frijns, J.J. Briaire, J.A. de Laat, Initial evaluation of the Clarion CII cochlear implant: speech perception and neural response imaging, Ear Hearing. 23 (2002) 184-197.

[10] C. Zierhofer, Multichannel cochlear implant with neural response telemetry. (2003) US Patent Nr. 6600955.

[11] D. Regan, Human brain electrophysiology, Elsevier Science, New York, 1989.

[12] W. Martin, C. Klop, A. Hartlooper, A New Method for Dealing with the Stimulus Artefact in Electrically Evoked Compound Action Potential Measurements, Acta Otolaryngol. 124 (2004) 137-143.

[13] P. Spitzer, C. Zierhofer, E. Hochmair, Algorithm for multi-curve-fitting with shared parameters and a possible application in evoked compound action potential measurements, Biomed Eng OnLine. 5 (2006) 1-8.

[14] M.D. Eisen, K.H. Franck, Electrically Evoked Compound Action Potential Amplitude Growth Functions and HiResolution Programming Levels in Pediatric CII Implant Subjects, Ear Hearing. 25 (2004) 528-538.

[15] R.N. Scott, L. McLean, P.A. Parker, Stimulus artefact in somatosensory evoked potential measurement, Med Biol Eng Comput. 35 (1997) 211-215.

[16] I. Alvarez, A. de la Torre, M. Sainz, Generalized alternating stimulation: A novel method to reduce stimulus artifact in electrically evoked compound action potentials, J Neurosci Meth. 165 (2007) 95-103.

[17] I. Alvarez, A. de la Torre, M. Sainz, An improved masker-probe method for stimulus artifact reduction in electrically evoked compound action potentials, J Neurosci Methods. 175 (2008) 143-147.

[18] C.J. Brown, P.J. Abbas, Electrically evoked whole-nerve action potentials: Data from human cochlear implant users, J Acoust Soc Am. 88 (1990) 1385-1391.

[19] C.A. Miller, P.J. Abbas, C.J. Brown, An improved method of reducing stimulus artifact in the electrically evoked whole-nerve potential, Ear Hearing. 21 (2000) 280-290.

[20] C. Frohne, M. Brendel, A. Bchnerm, Artefact reduction in Neural Response Imaging via a modified stimulation signal, 4th International Symposium and Workshops Objectives Measures in Cochlear Implants, Hannover, 2005.

[21] M. Sainz, A. de la Torre, I. Alvarez, Processing of artifact in electrically evoked action potentials, 4th International Symposium and Workshops Objectives Measures in Cochlear Implants, Hannover, 2005.

[22] H. Schoesser, C. Zierhofer, E.S. Hochmair, Measuring electrically evoked compound action potentials using triphasic pulses for the reduction of the residual stimulation artifact, Conference on Implantable Auditory Protheses, Asilomar, 2001.

[23] M. Knaflitz, R. Merletti, Suppression of stimulus artifacts from myoelectric-evoked potential recordings, IEEE Trans Biomed Eng. 35 (1988) 758-763.

[24] R.J. Roby, E. Lettich, A simplified circuit for stimulus artifact suppression, Electroenceph Clin Neurophys. 39 (1975) 85-87.

[25] D.T. O'Keeffe, G.M. Lyons, A.E. Donnelly, Stimulus artifact removal using a software-based two-stage peak detection algorithm, J Neurosci Meth. 109 (2001) 137-145.

[26] C.A. Miller, P.J. Abbas, J.T. Rubinstein, Electrically evoked compound action potentials of guinea pig and cat: responses to monopolar, monophasic stimulation, Hear Res. 119 (1998) 142-154.

[27] T. Ragheb, L.A. Geddes, Electrical properties of metallic electrodes, Med Biol Eng Comput. 28 (1990) 182-186.

[28] L.A. Geddes, Historical evolution of circuit models for the electrode-electrolyte interface, Ann Biomed Eng. 25 (1997) 1-14.

[29] J.D. Gibbons, Nonparametric Statistical Inference (2nd edition, M. Dekker, 1985).

Table Legends

- Table 1. Comparison of different methods of both stimulus and blanking artifact reduction for 126 ECAP recordings.

Figure Legends

- Figure 1. Two stimulation patterns used for the ECAP recording system integrated in the Pulsar CI^{100} cochlear implant.
- Figure 2. Instance of recordings associated with anodic-cathodic (R_{ac}) and cathodic-anodic (R_{ca}) biphasic stimulation pulses increasing the stimulation level. The difference between these two recordings is also shown.
- Figure 3. Instances of ECAP recordings with different quality units assigned by an expert (Q_E), in the range 0–10 [16].
- Figure 4. Recordings associated with conventional (R_{alt}) and generalized (R_{galt}) alternating stimulation. Recordings using anodic-cathodic (R_{ac}) and cathodic-anodic (R_{ca}) biphasic pulses as stimulation and the blanking template (R_{blank}) used in the proposed conventional (+b) and generalized (+gb) blanking artifact reduction methods are shown. The values of the α and β weights are also shown.
- Figure 5. Four ECAP recordings acquired with conventional alternating stimulation (R_{alt}) and generalized alternating stimulation (R_{galt}), combined them with the conventional (+b) and generalized (+gb) proposed blanking artifact reduction techniques. The automatically estimated quality (Q) for each method is also shown.

Conflicts of Interest

None declared

Table

Methods	N	μ_Q	σ_Q	μ_α	σ_α	μ_β	σ_β	Acquisition Time (s)	Computational Load (s)
alt	126	3.60	2.99	0.5	0	0	0	2	-
alt+b	126	5.81	2.69	0.5	0	-1	0	3	-
alt+gb	126	7.22	2.61	0.5	0	-1.08	0.48	3	0.054
galt	126	6.72	2.72	0.63	0.22	0	0	2	0.036
galt+b	126	7.73	2.37	0.53	0.19	-1	0	3	0.036
galt+gb	126	8.56	1.94	0.52	0.21	-0.83	0.72	3	1.08

Table 1.

Figure1

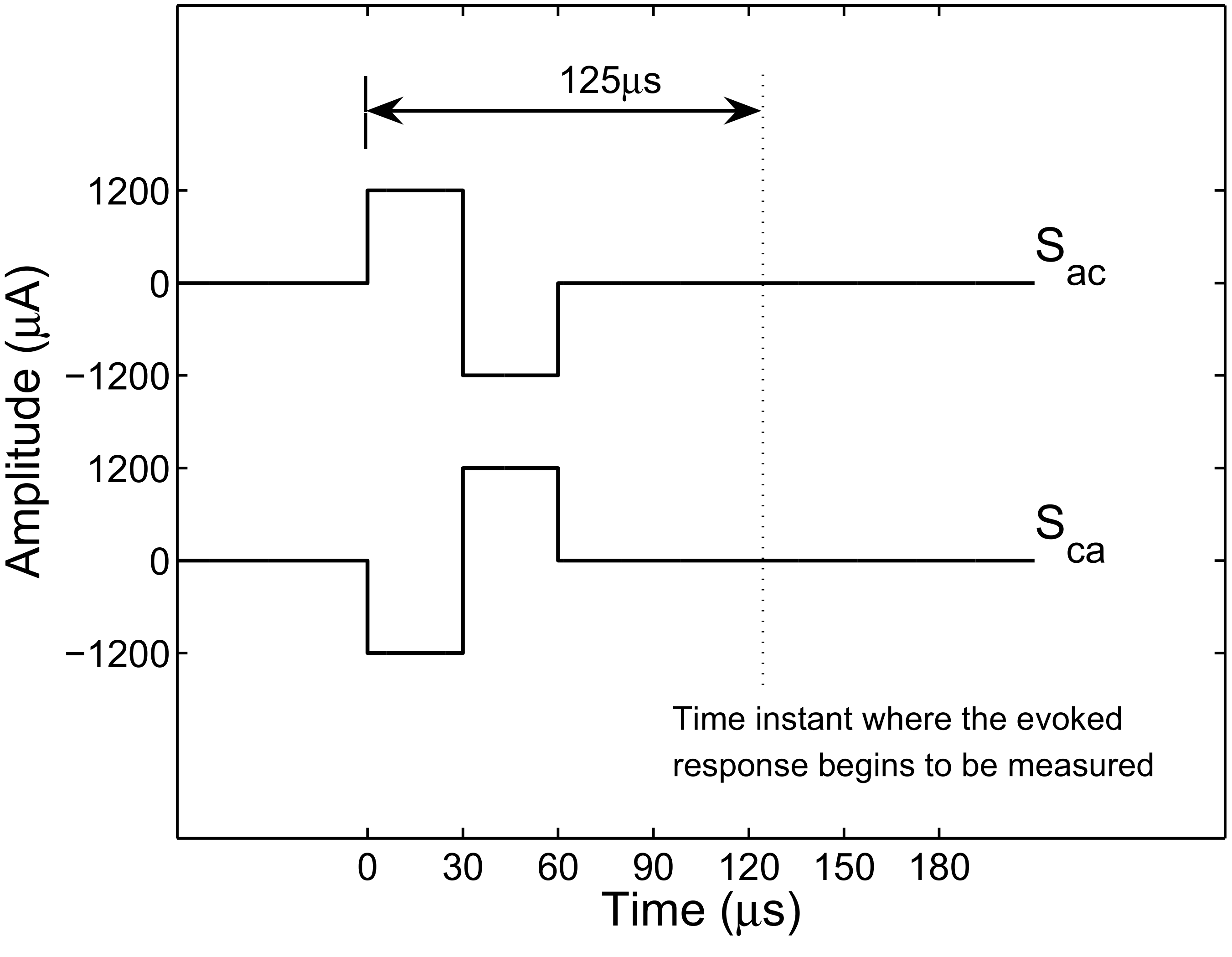
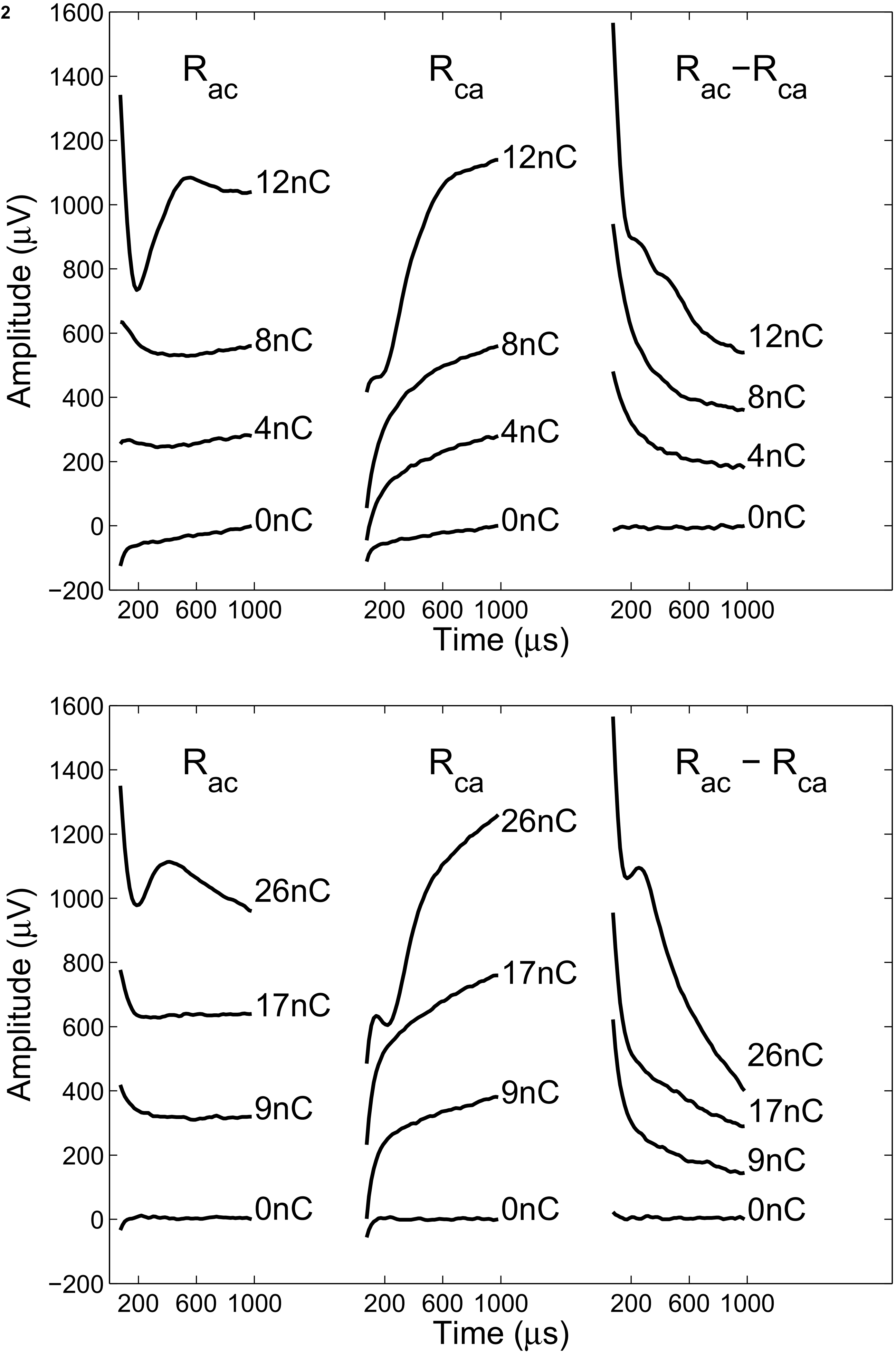
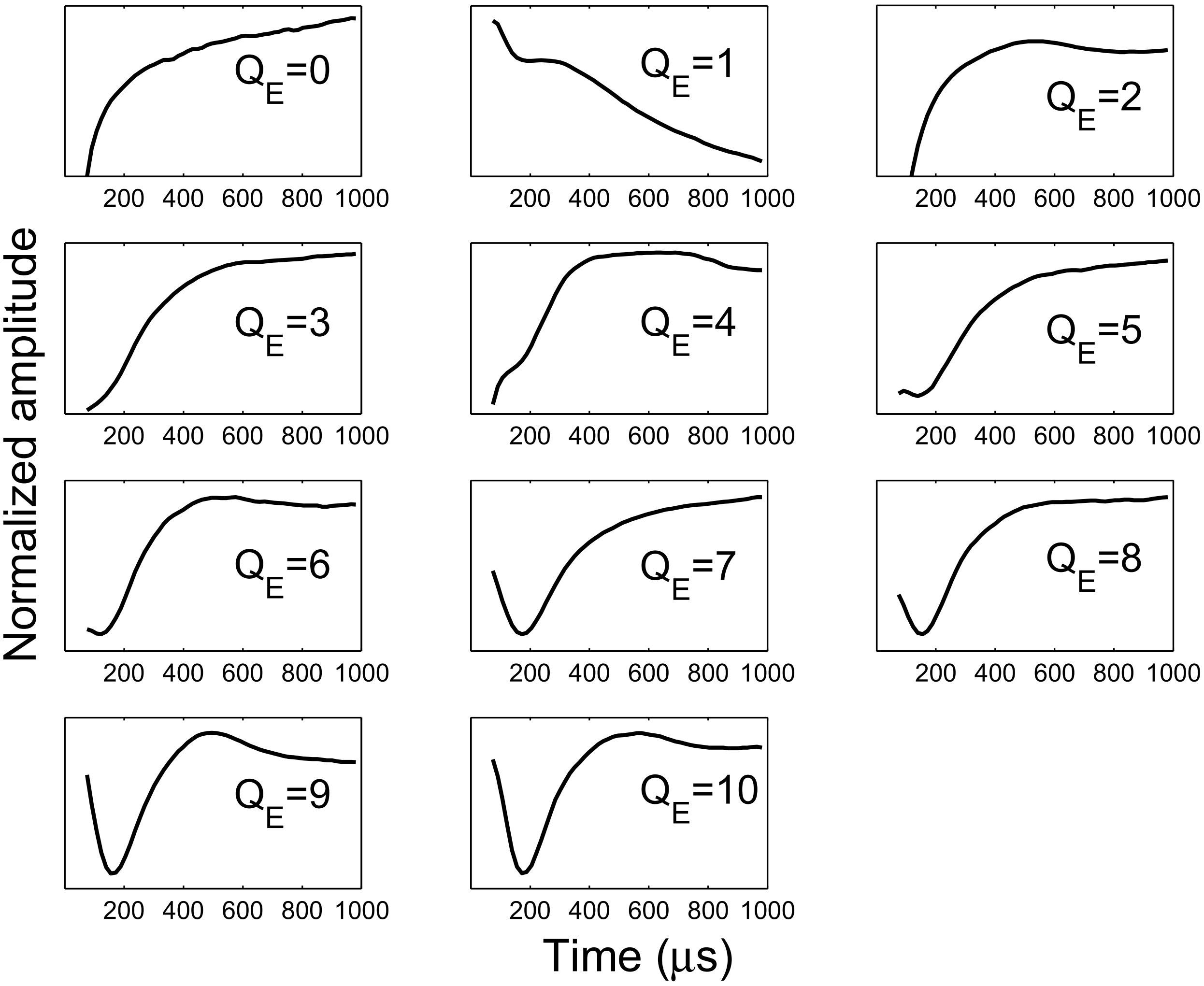

125μs
1200
0
−1200
1200
0
−1200
Amplitude (μA)
S_{ac}
S_{ca}
Time instant where the evoked
response begins to be measured
0
30
60
90
120
150
180
Time (μs)

Figure2



R_{ac}
R_{ca}
$R_{ac}-R_{ca}$
12nC
8nC
4nC
0nC
Amplitude (µV)
Time (µs)
1600
1400
1200
1000
800
600
400
200
0
−200
200
600
1000
R_{ac}
R_{ca}
$R_{ac} - R_{ca}$
26nC
17nC
9nC
0nC
Amplitude (µV)
Time (µs)

Figure3


Normalized amplitude
Time (μs)
Q_E=0
Q_E=1
Q_E=2
Q_E=3
Q_E=4
Q_E=5
Q_E=6
Q_E=7
Q_E=8
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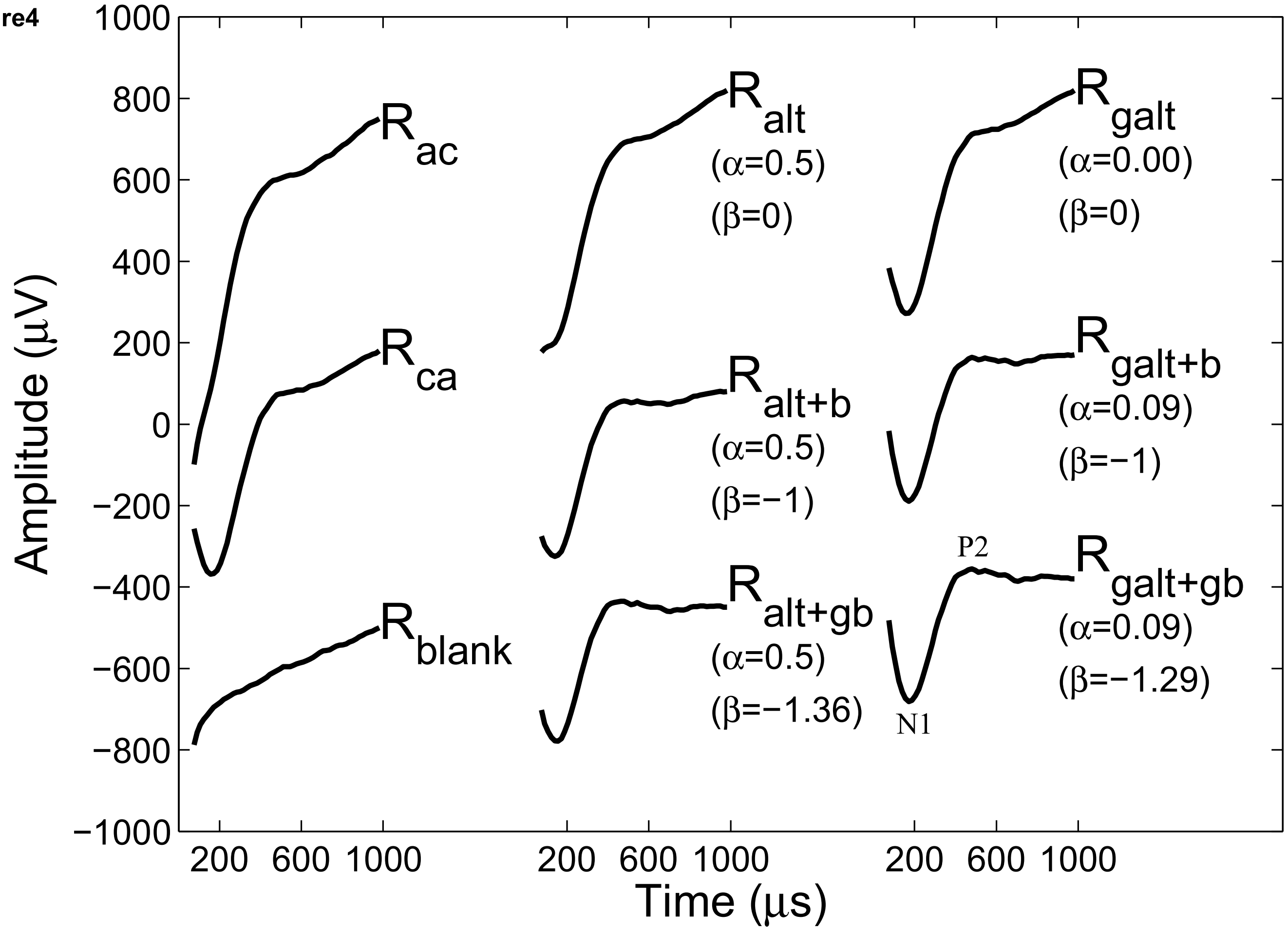
Q_E=10
200 400 600 800 1000

Figure4


1000
800
600
400
200
0
−200
−400
−600
−800
−1000
Amplitude (μV)
R_ac
R_ca
R_blank
R_alt
(α=0.5)
(β=0)
R_alt+b
(α=0.5)
(β=−1)
R_alt+gb
(α=0.5)
(β=−1.36)
R_galt
(α=0.00)
(β=0)
R_galt+b
(α=0.09)
(β=−1)
P2
R_galt+gb
(α=0.09)
(β=−1.29)
N1
200 600 1000
200 600 1000
200 600 1000
Time (μs)

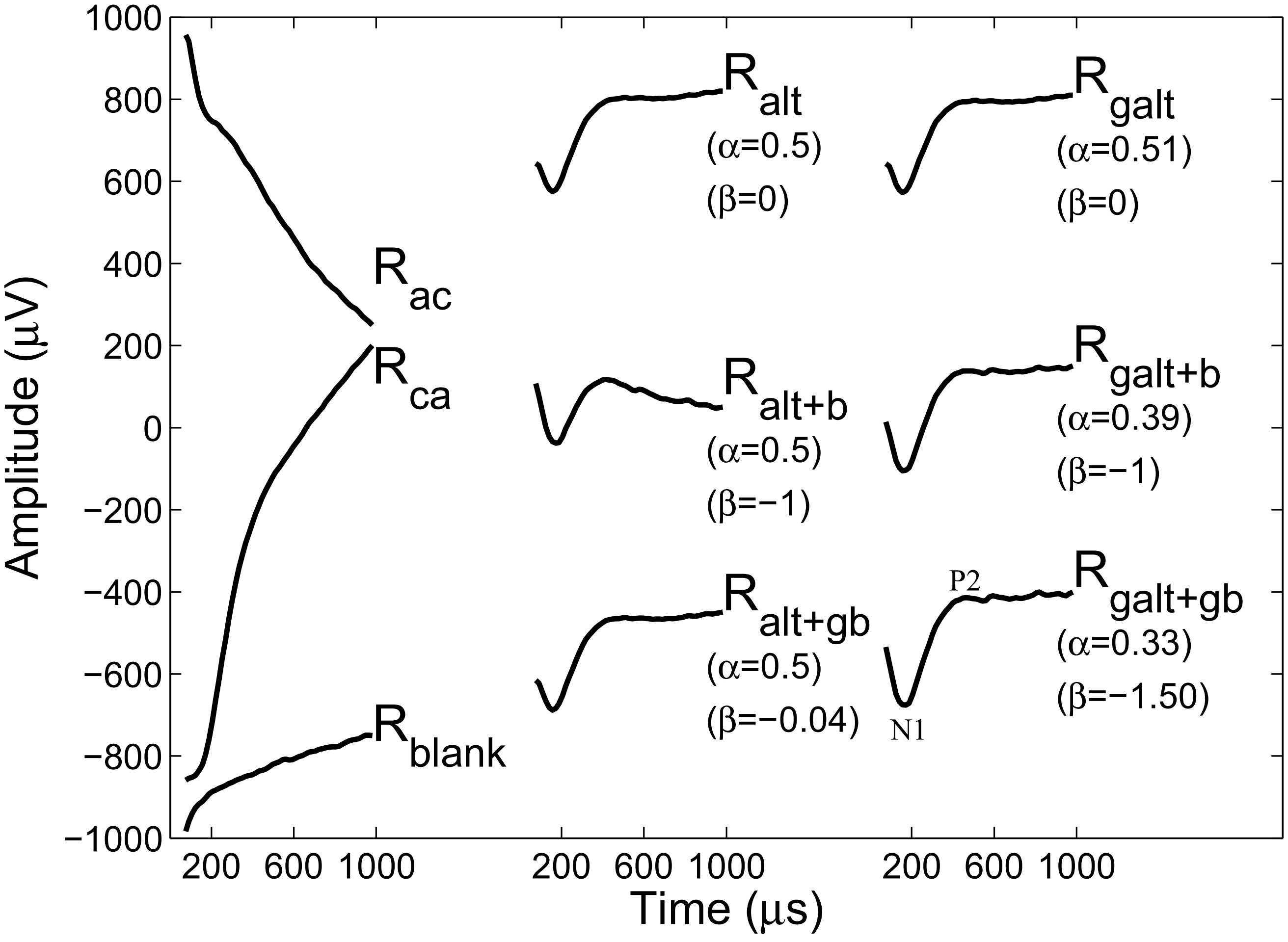
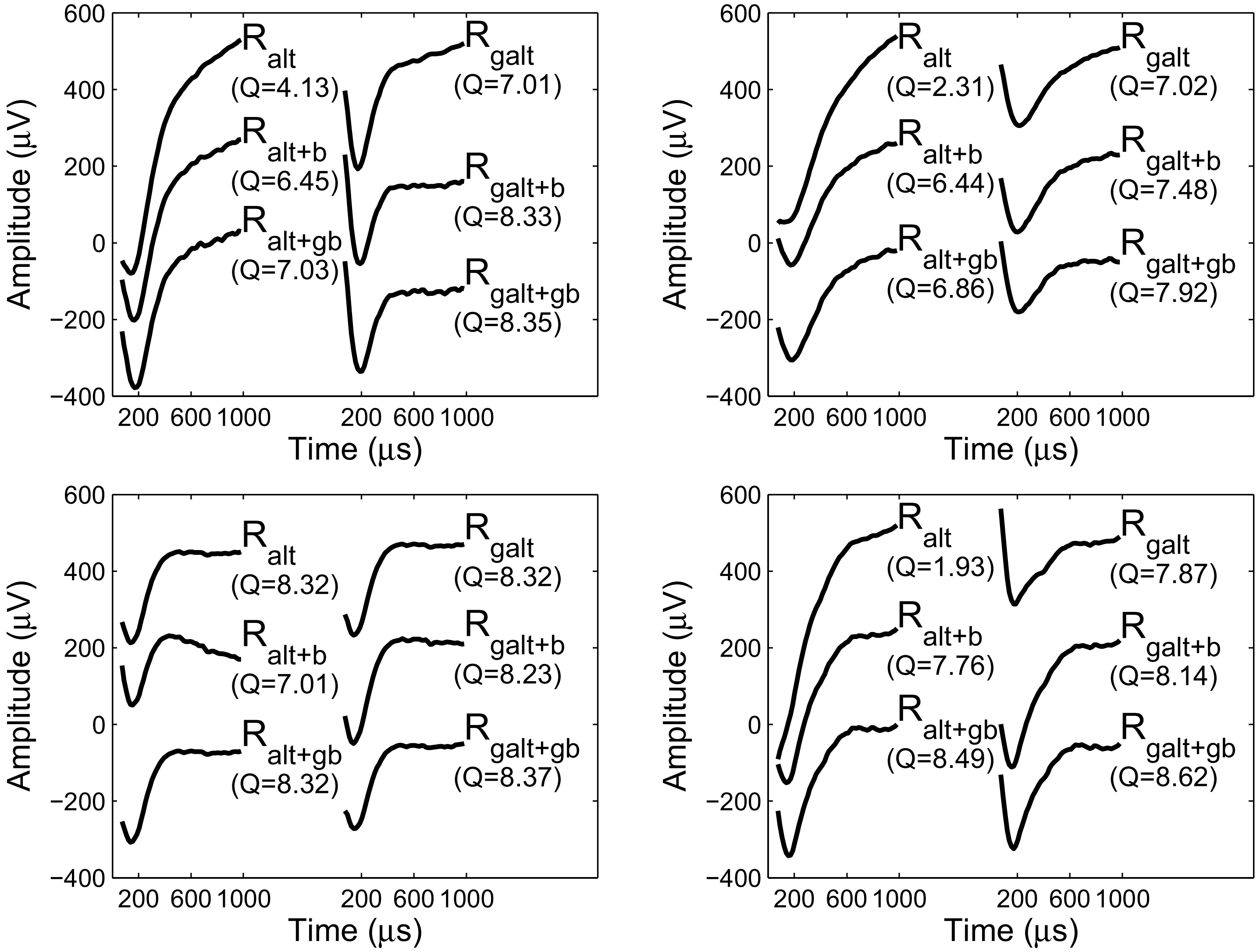

1000
800
600
400
200
0
−200
−400
−600
−800
−1000
Amplitude (μV)
R_ac
R_ca
R_blank
R_alt
(α=0.5)
(β=0)
R_alt+b
(α=0.5)
(β=−1)
R_alt+gb
(α=0.5)
(β=−0.04)
R_galt
(α=0.51)
(β=0)
R_galt+b
(α=0.39)
(β=−1)
P2
R_galt+gb
(α=0.33)
(β=−1.50)
N1
200 600 1000
200 600 1000
200 600 1000
Time (μs)

Figure5


Amplitude (μV)
Time (μs)
600
400
200
0
−200
−400
200 600 1000
R_{alt} (Q=4.13)
R_{alt+b} (Q=6.45)
R_{alt+gb} (Q=7.03)
R_{galt} (Q=7.01)
R_{galt+b} (Q=8.33)
$R_{galt+gb}$ (Q=8.35)
R_{alt} (Q=2.31)
R_{alt+b} (Q=6.44)
R_{alt+gb} (Q=6.86)
R_{galt} (Q=7.02)
R_{galt+b} (Q=7.48)
$R_{galt+gb}$ (Q=7.92)
R_{alt} (Q=8.32)
R_{alt+b} (Q=7.01)
R_{alt+gb} (Q=8.32)
R_{galt} (Q=8.32)
R_{galt+b} (Q=8.23)
$R_{galt+gb}$ (Q=8.37)
R_{alt} (Q=1.93)
R_{alt+b} (Q=7.76)
R_{alt+gb} (Q=8.49)
R_{galt} (Q=7.87)
R_{galt+b} (Q=8.14)
$R_{galt+gb}$ (Q=8.62)