# Ninth Quarterly Progress Report

April 1 through June 30, 2004
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# **Speech Processors for Auditory Prostheses**

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# I. Introduction

The main objective of this project is to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, such processors will represent the information content of speech in a way that can be perceived and utilized by implant patients. An additional objective is to record responses of the auditory nerve to a variety of electrical stimuli in studies with patients. Results from such recordings can provide important information on the physiological function of the nerve, on an electrode-by-electrode basis, and can be used to evaluate the ability of speech processing strategies to produce desired spatial or temporal patterns of neural activity.

Work and activities in this quarter included:

- Studies April 19-23 with subject NP-8, implanted with an experimental version of the Nucleus device that provides percutaneous access to a Contour electrode array. The studies included consonant identification tests with a variety of experimental processors, and melody identification tests with a selected subset of processors.
- Studies May 3-7 with German Med-El C40+/TEMPO+ subject ME-20, a routine user of combined electrical and contralateral aided acoustic stimulation (EAS). This subject has considerable residual acoustic hearing sensitivity up to at least 1 kHz in both ears. In addition to speech reception comparisons with a variety of combined stimulation designs, studies during this visit included pitch ranking, pitch scaling, pitch matching, and pitch DL measurements relating electrically and acoustically stimulated pitch percepts in the same ear.
- Presentation by Wilson at the *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13.
- Presentation by Wilson at the Med-El Satellite Symposium, in conjunction with the *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13.
- Further studies May 24-25 with Nucleus percutaneous subject NP-8. Studies included tests of word identification in CUNY sentences with many of the processors investigated during that subject's preceding visit.
- Studies June 7-8 with Nucleus percutaneous subject NP-6, including consonant identification tests with a variety of CIS processor configurations.

In addition to the above-mentioned activities, work continued on analyses of previously collected data and on the preparation of manuscripts for publication

In the present report we present results from intracochlear evoked potential studies using phase-separated balanced biphasic pulses as stimuli.

Results from other studies, including those completed during the current quarter, will be presented in future reports.

## II. Intracochlear potentials evoked by electrical stimulation with phase-separated balanced biphasic pulses

### Introduction

To achieve charge balance in intracochlear stimuli, equal-amplitude biphasic current pulses are the most common shape employed by cochlear implant speech processors. Because the two phases of the biphasic pulse counteract each other, the threshold for stimulation of a nerve fiber with a biphasic pulse is generally higher than that of a cathodic pulse alone. For example, for a biphasic pulse with a leading cathodic phase, the initial phase will depolarize the fiber and the following anodic phase will partially repolarize it. If the phase durations are small, the repolarization can occur before excitation and can increase the excitation threshold. Likewise, an anodic leading pulse of short duration tends to hyperpolarize the fiber, requiring a larger cathodic phase to reach a depolarization level sufficient for activation of the fiber. If a temporal gap occurs between the two phases of the biphasic pulse, the opposing effect of the two stimulus phases is reduced. In cochlear implants, psychophysical studies using split phase biphasic pulses -- biphasic pulses with a temporal delay between the anodic and cathodic phases known as an interpulse gap (IPG) -- have shown that an exponential increase in current level is necessary to maintain equal loudness as the IPG is decreased (McKay and Henshall, 2003). By introducing an IPG, it is possible to reduce the stimulus magnitude necessary to reach a desired loudness. This strategy may be useful for increasing battery life in speech processors.

A cathodic pulse typically stimulates neurons at a lower threshold than an anodic pulse and at a different site of excitation. Cathodic pulses directly depolarize the neural tissue at the site nearest the electrode. Current circuits resulting from the stimulus hyperpolarize the tissue in the adjacent regions. However, the resulting hyperpolarization is typically of lower magnitude than the direct depolarization and at threshold or higher levels is not sufficient to stop the spread of excitation. Anodic pulses stimulate at "virtual cathode" sites (van den Honert and Stypulkowski, 1987; Rattay, 1990). The anodic pulse hyperpolarizes the neural tissue closest to the electrode. The current circuits resulting from the hyperpolarization result in a lower magnitude depolarization in the adjacent regions. If the stimulus magnitude is sufficiently large, the adjacent depolarization may be large enough to reach threshold. With anodic pulses, excitation is initiated not in the regions closest to the electrode, but in the adjacent tissue. For this reason, cathodic stimuli may be advantageous for focal stimulation of neural tissue adjacent to the stimulating electrode.

To further understand the response of the cochlear nerve to phase-separated biphasic pulses, we measured the intracochlear evoked potential (IEP) in response to traditional and phase-separated biphasic pulses.

### Methods

For this preliminary study, IEPs were measured through percutaneous electrodes in two patients with Ineraid cochlear implants, subjects SR-3 and SR-9. Electrical stimuli were delivered through a cochlear implant electrode using the implant ground electrode in the temporalis muscle as a return. Intracochlear potentials were measured differentially using a custom-built amplifier (van den Honert *et al.*, 1997) between an unstimulated electrode and an electrode placed on the mastoid with a wrist electrode present for measuring the reference body potential. The amplifier is comprised of a cascade of four low gain (10x) amplifier stages for a maximum gain of 10,000. Gain is controlled by bypassing unneeded stages. A passive diode clamp at the input of each stage permits it to operate linearly up to an output level of about 5V, but prevents any stage from saturating. At a gain of 1000, the amplifier recovers from a 1V artifact pulse to 10 μV (referred to input) in 10 μs. The amplifier is isolated by a custom optical isolator built around a bare LED/photodiode package. The isolator design provides full power bandwidth of 500 kHz at unity gain with low output noise (3 mV p-p).

A diagram of the stimulus used in the study is shown in Figure. 1. A series of 4 stimuli were initiated at 0, 20, 40, and 60 ms. The initial stimulus was an anodic leading biphasic pulse with no separation between the pulse phases (P1). The second stimulus was a cathodic leading biphasic pulse with no pulse separation (P2). The 3rd stimulus was an anodic leading biphasic pulse with a 3 ms separation between pulse phases (P3). The final stimulus was a cathodic leading biphasic pulse with a 3 ms IPG (P4). Each stimulus phase was 32 μs in duration.

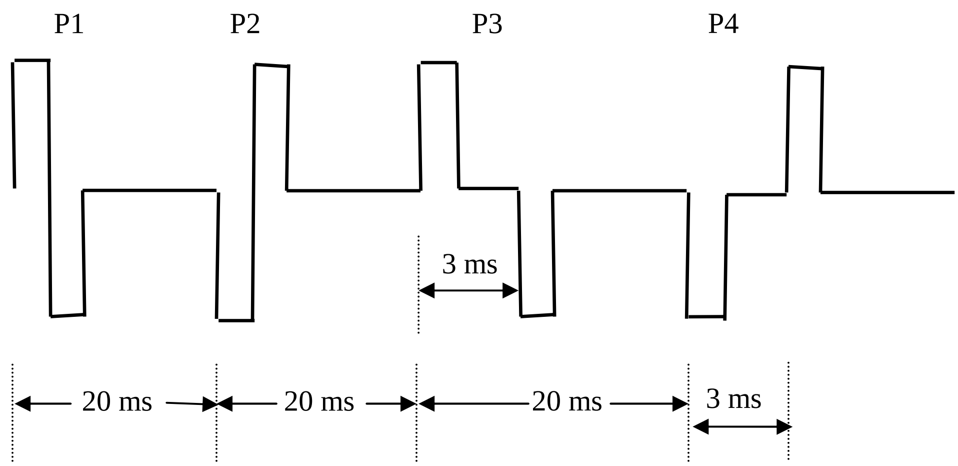


Figure 1: Diagram of the stimulus used for the studies (not to scale). Four biphasic pulses were initiated at 20 ms intervals. P1, the first biphasic pulse, was an anodic-leading biphasic pulse with no IPG. P2, the second biphasic pulse, was a cathodic-leading biphasic pulse with no IPG. P3, the third biphasic pulse, was an anodic-leading biphasic pulse with a 3 ms IPG. P4, the fourth biphasic pulse, was a cathodic-leading biphasic pulse with a 3 ms IPG.

Each of the four pulses in a stimulus was presented at the same stimulus amplitude. IEPs were recorded for stimulus magnitudes ranging from threshold to a comfortable loudness level.

Two methods of artifact reduction were used in the studies, alternation and scaling. Alternation is a commonly used method of artifact reduction for IEP measurement. Using this technique, the stimulus polarity is alternated with each successive presentation. The rationale for this method is that the artifact will change polarity with each successive pulse while the biological response will remain constant. A long-term average of the signals will reduce the artifact while the biological response remains constant.

The scaling method of artifact subtraction assumes that the stimulus artifact scales linearly with stimulus magnitude. Using this assumption, the response to a subthreshold stimulus that does not exhibit a biological component can be linearly scaled and subtracted from the magnitude of a suprathreshold response. The biological component remains while the artifact component is reduced. The scaling technique used is this study allows for the possibility of a biological component in the subthreshold recording. The difference between the subthreshold responses to stimuli of opposite polarity is computed. Because the stimulus artifacts in response to the two stimuli are also of opposite polarity, the difference produces a signal of twice the artifact magnitude while canceling a possible biological component. For anodic leading stimuli, the equation for artifact reduction was:

$$AF_{red} = AF_{raw} - \frac{AF_{sub} - CF_{sub}}{2} * \frac{I_{raw}}{I_{sub}}$$

where $AF_{red}$ is the reduced anodic first IEP with artifact subtracted
$AF_{raw}$ is the measured anodic first IEP with artifact
$AF_{sub}$ is the subthreshold, anodic first IEP
$CF_{sub}$ is the subthreshold, cathodic first IEP
$I_{raw}$ is the stimulus level of the measured IEP
$I_{sub}$ is the stimulus level of the subthreshold IEP

For cathodic first IEPs, the artifact was subtracted in the same manner:

$$CF_{red} = CF_{raw} + \frac{AF_{sub} - CF_{sub}}{2} * \frac{I_{raw}}{I_{sub}}$$

where $CF_{red}$ is the reduced cathodic first IEP with artifact subtracted, and $CF_{raw}$ is the measured cathodic first IEP with artifact.

Stimuli were presented multiple times and the resulting evoked potentials averaged. For single polarity studies, the responses to 100 presentations of the stimulus were averaged with the exception of the subthreshold response used for artifact subtraction for which 500 stimulus responses were averaged. For alternating polarity stimuli, the responses to 200 presentations of the stimulus were averaged.

## Results

Figure 2. shows a typical IEP obtained with our recording amplifier. For this recording, alternation of polarity on each successive pulse was used as a means of reducing the stimulus artifact. The sharp straight lines that go off the scale of the graph are the result of the stimulus artifact. Following the artifact, N1 and P2 waveforms are present in the IEP recording as shown. Prior modeling results (Cartee *et al.*, 2001; Miller *et al.*, 1998) have shown that a P1 waveform (a positive leading phase) is only generated when the excitation site is at least 4 nodes (approximately 1 mm) peripheral to the recording site. It is necessary for the excitation to propagate past the recording site in order to produce the P1 waveform. If the site of excitation is directly beneath the recording electrode, only the N1 and P2 waveforms are generated. An initial P1 waveform has been recorded from electrodes placed on the base of the nerve trunk external to the cochlea in response to cathodic, but not anodic, stimulation (Miller *et al.,* 1999). That result was taken to indicate that the site of excitation for cathodic stimuli was intracochlear while that of anodic stimuli was extracochlear.

Figures 3-6 show the IEPs for a series of increasing stimulus amplitudes recorded from subject SR-3 using electrode 3 for stimulation and electrode 4 as the recording electrode. The figures show the response to each of the four pulse configurations of the stimulus in order. Figure 3 shows the response to an anodic leading biphasic pulse (P1) while Figure 4 shows the response to a cathodic leading pulse (P2). Figure 5 shows the response to an anodic leading biphasic pulse with a 3 ms IPG (P3), and Figure 6 shows the response to a cathodic leading biphasic pulse with a 3 ms IPG (P4).

The shape of the IEP for both biphasic pulses without an interpulse gap is similar. The main difference is an increased magnitude of the N1 phase of the IEP for an anodic leading biphasic pulse over that of the cathodic leading biphasic pulse. For an anodic leading pulse with a 3 ms IPG (Figure 4), the anodic phase of the pulse produces a large N1 wave followed by a P2 wave. For the cathodic phase of the stimulus, only the P2 portion of the IEP is clearly visible. In Figure 5, when the order of polarities was reversed, similar behavior was measured for each phase.

Figure 7 demonstrates that the IEP recorded from the cathodic phase of the biphasic pulse with a 3 ms IPG is similar whether the cathodic phase is the leading phase of the biphasic pulse or the trailing phase for SR-3’s electrode 3-4 (stimulate on 3; record on 4) combination. The figure shows the overlapping responses for the IEP recorded from a cathodic first biphasic pulse with a 3 ms IPG and the cathodic phase of an anodic first biphasic pulse with a 3 ms IPG shifted in time so that the initiation time of each of the cathodic pulses aligns. Very little difference in the two responses can be seen. Figure 8 shows similar data for the isolated anodic phases of the anodic leading and anodic trailing phases of a biphasic pulse with 3 ms IPG. Again, the recorded IEPs demonstrate a great deal of similarity. The same holds true for electrode combinations 5-6 and 1-2 as shown in Figures A-1 - A-4 in the Appendix A.

The fact that the IEP exhibits little or no change due to refractoriness at an interpulse interval (IPI) of 3 ms is not surprising since prior measurements of IEPs demonstrated no change

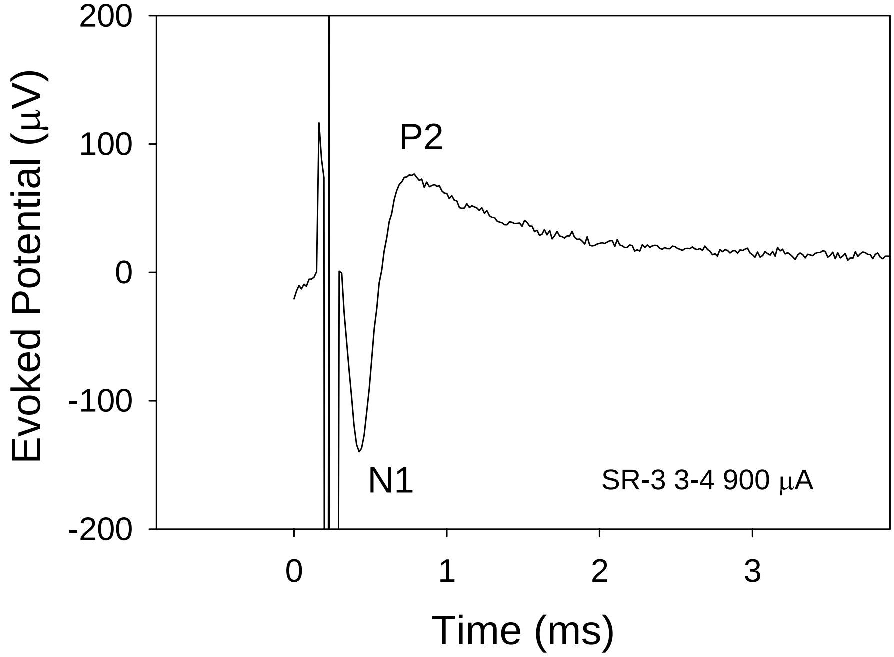


Fig. 2: Illustration of the N1 and P2 evoked potentials typically recorded with intracochlear stimulation using alternating polarity as a means of artifact reduction.

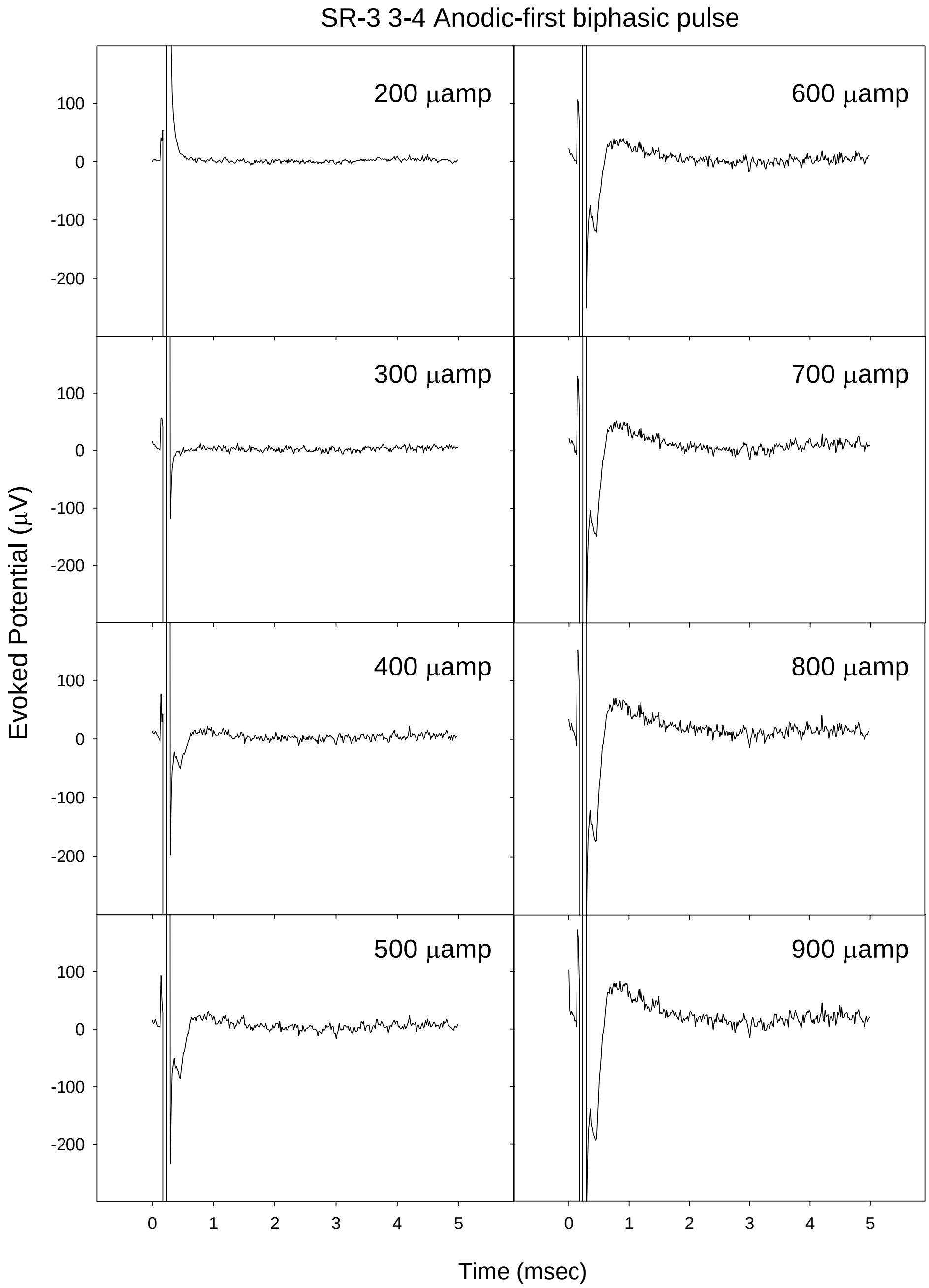


Fig. 3: IEPs recorded in response to an anodic-first biphasic pulse without an IPG for increasing stimulus amplitudes. Stimulus artifact was reduced using the scaling method of artifact subtraction.

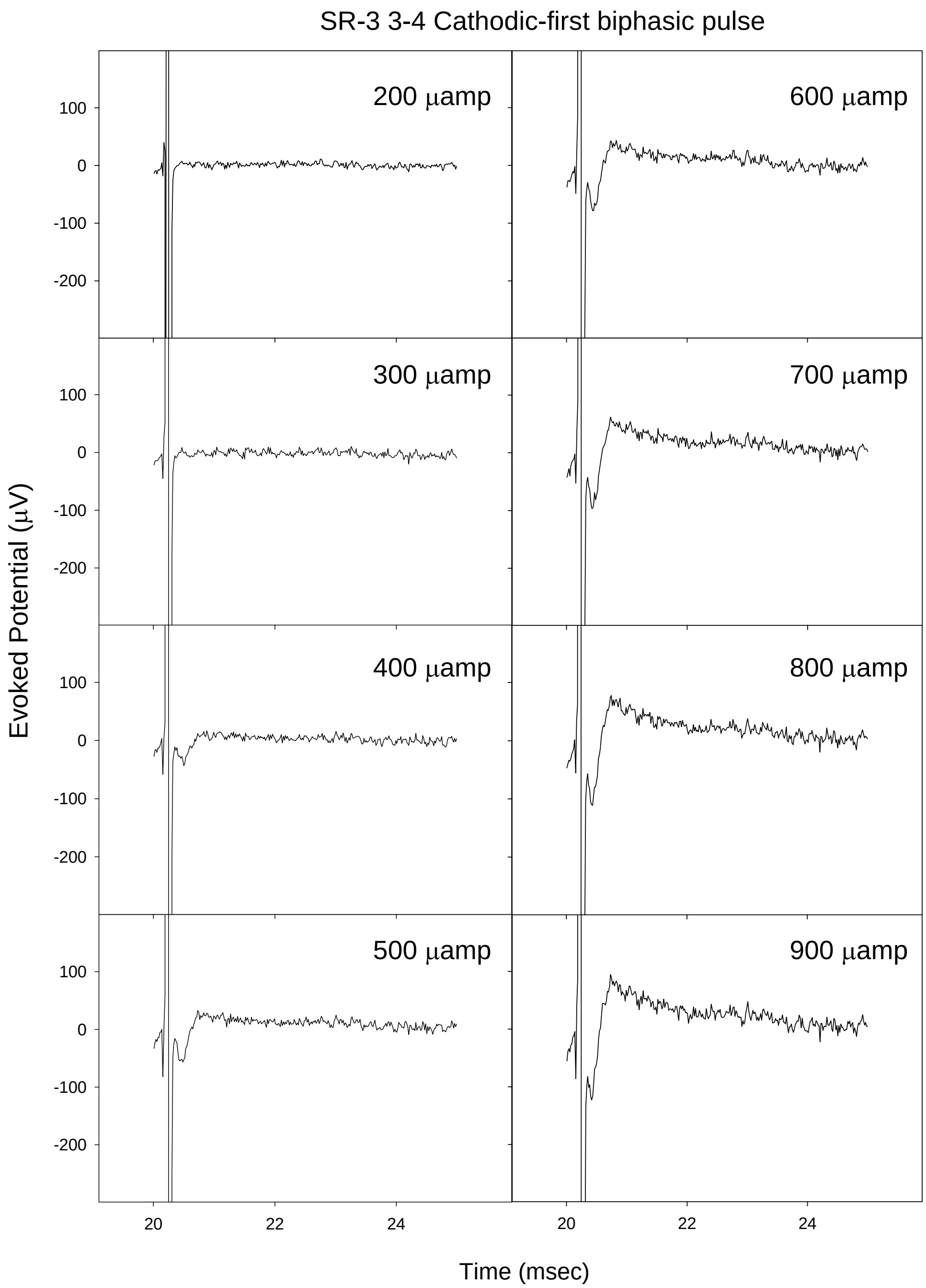


Fig. 4: IEPs recorded in response to a cathodic-first biphasic pulse without an IPG for increasing stimulus amplitudes. Stimulus artifact was reduced using the scaling method of artifact subtraction.

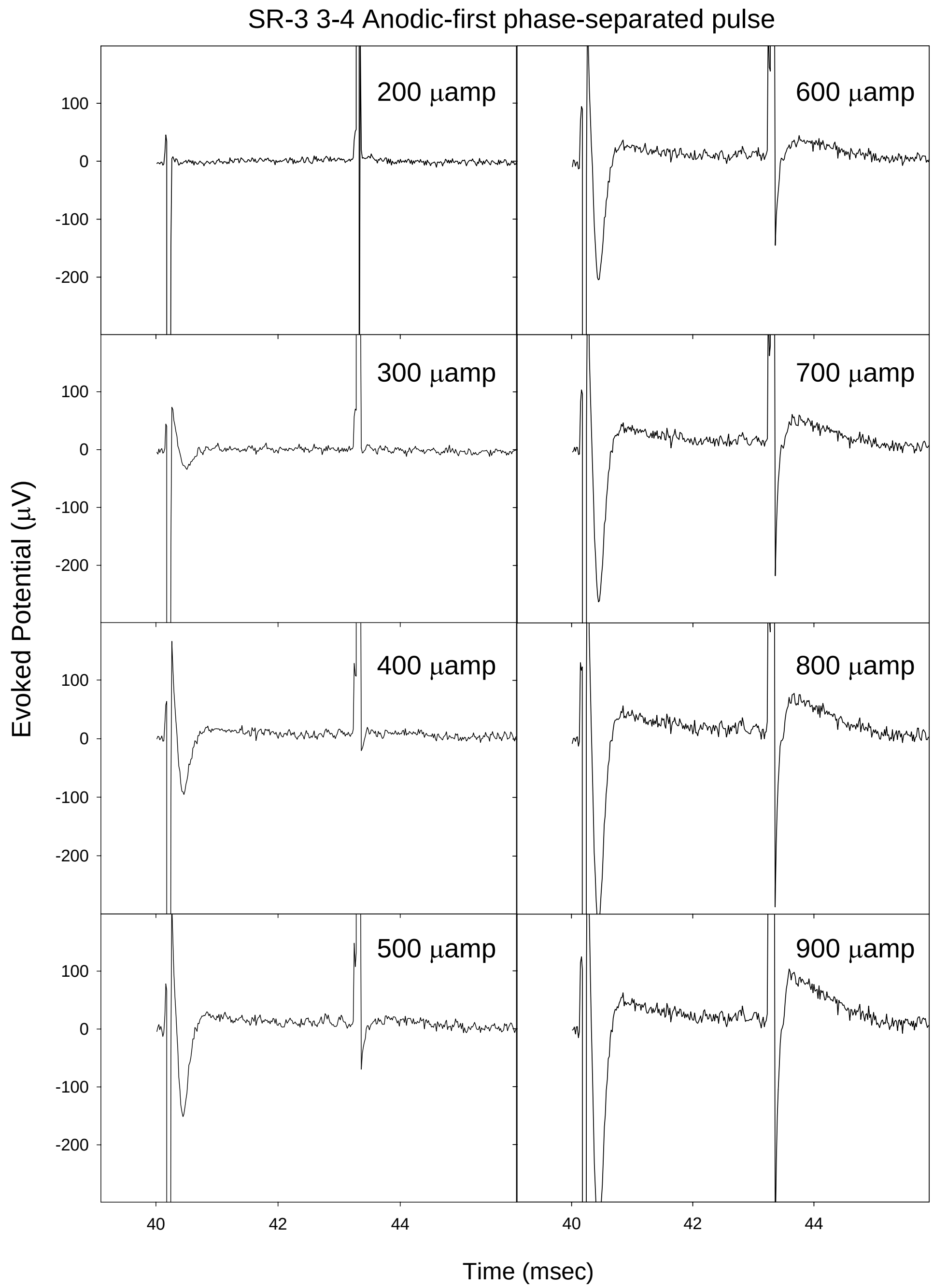


Figure 5: IEPs recorded in response to an anodic-first biphasic pulse with a 3 ms IPG for increasing stimulus amplitudes. Stimulus artifact was reduced using the scaling method of artifact subtraction.

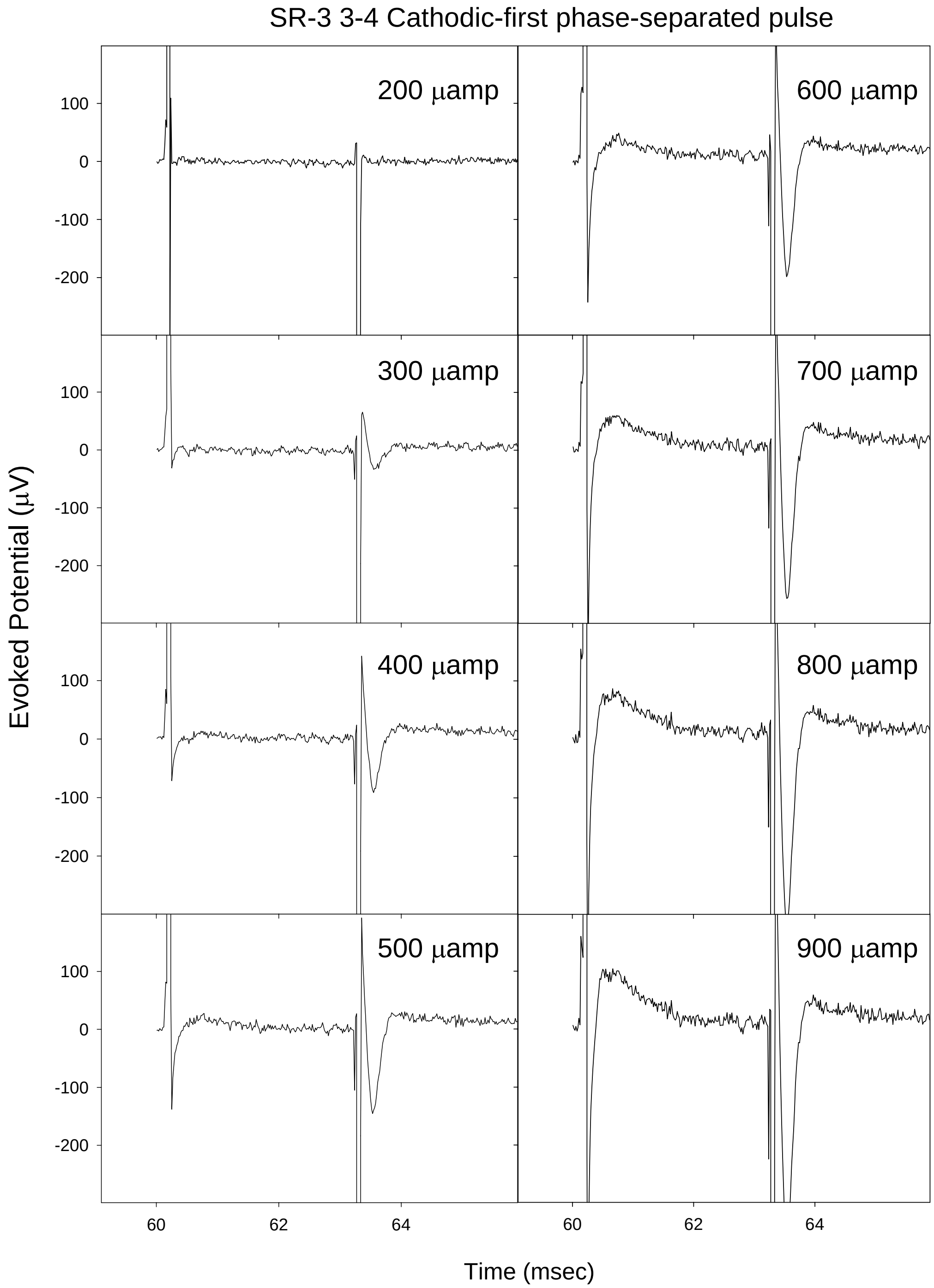


Fig. 6: IEPs recorded in response to a cathodic-first biphasic pulse with a 3 ms IPG for increasing stimulus amplitudes. Stimulus artifact was reduced using the scaling method of artifact subtraction.

SR-3 3-4 Cathodic-first and cathodic-second phase-separated responses

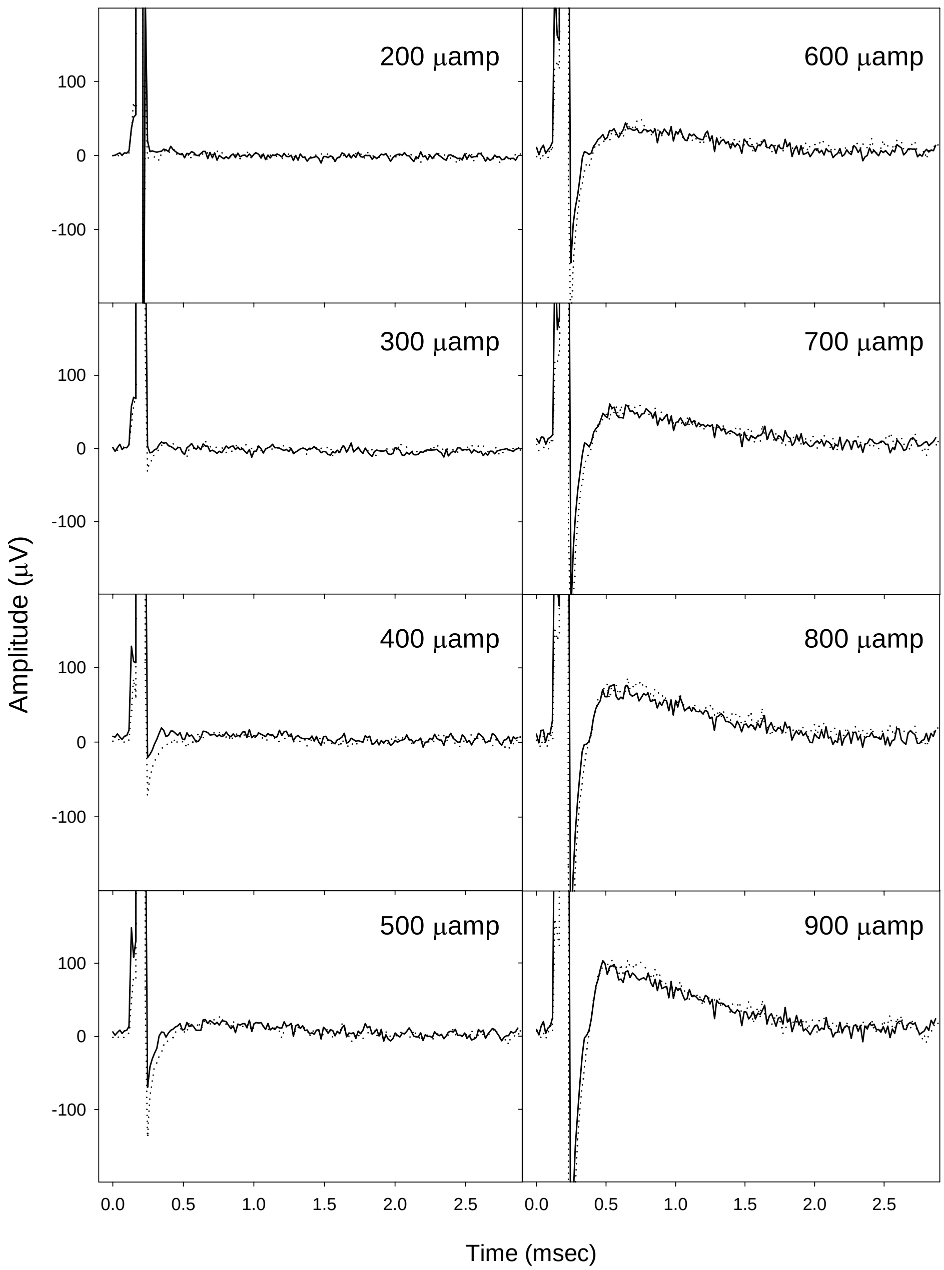


Fig. 7: IEPs recorded in response to the intial cathodic phase of a cathodic-leading biphasic pulse (dashed line) with a 3 ms IPG, and the final cathodic phase of an anodic-leading biphasic pulse with a 3 ms IPG (solid line).  Stimulus artifact was reduced using the scaling method of artifact subtraction.

SR-3 3-4 Anodic-first and anodic-second phase-separated responses

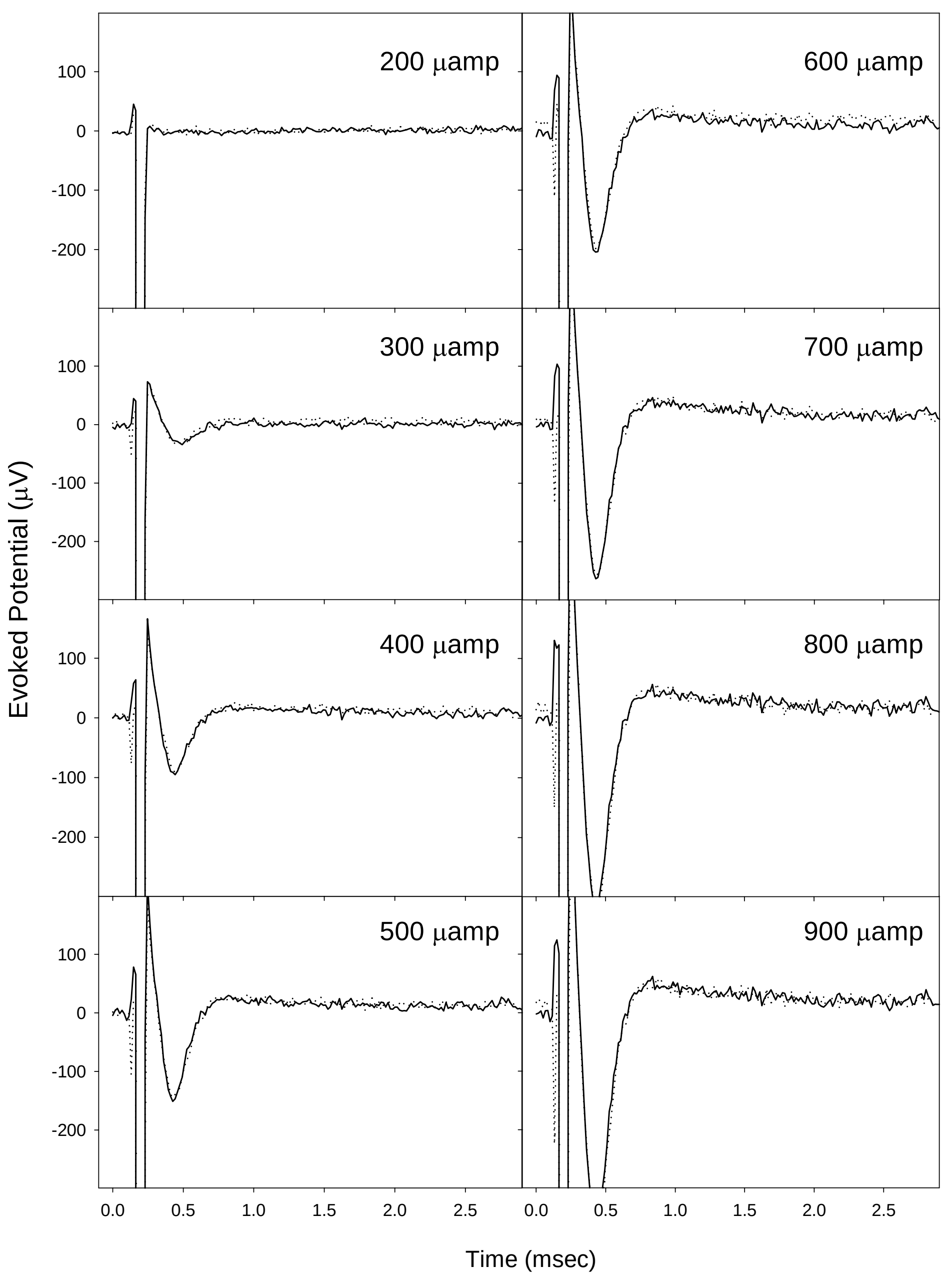


Fig. 8: IEPs recorded in response to the intial anodic phase of an anodic-leading biphasic pulse (solid line) with a 3 ms IPG, and the final anodic phase of a cathodic-leading biphasic pulse with a 3 ms IPG (dashed line). Stimulus artifact was reduced using the scaling method of artifact subtraction.

in the IEP magnitude for pulse rates of 401 pps or less while higher pulse rates exhibited an alternation of IEP magnitude attributed to refractory behavior (Rubenstein *et al*., 1999).

While the similarity between each of the anodic phases of P3 and P4 and each of the cathodic phases of P3 and P4 holds for each electrode combination tested with subject SR-3, the same was not true with subject SR-9. Examination of the raw signals without artifact subtraction revealed the difference. Figure 9 shows the raw signals recorded for each electrode combination tested with SR-3. In each case, the raw signals have been scaled to be equivalent to the maximum stimulus amplitude. For the scaling method of artifact subtraction to be valid, the subthreshold artifact (the raw signal in the absence of a biological component) must scale linearly. For subject SR-3, the assumption of linearity holds. The last 15 samples recorded following stimulation with the first phase of the phase-separated stimulus revealed that the final, scaled signals differed from the scaled signal used for artifact subtraction by 36 μV or less. Similar scaled raw signals for SR-9 are shown in Figure 10. For stimulation with SR-9's 3-4 combination, the difference between the scaled signals could be as large as 140 μV and as large as 76 μV for combination 2-3. At the end of both phases of the phase-separated pulse, the difference between the scaled signal used for artifact signal and the other scaled signals was never greater than 44 μV. Given the smaller amplitude of IEPs recorded from SR-9 as compared to those recorded from SR-3, the error in the assumption of linearity of the artifact is unacceptable.

We believe the difference between the linearity of the subthreshold responses recorded from SR-3 and SR-9 may be due to a small current leakage between electrodes in SR-9. During the gap between phases of the phase-separated pulse, the electrode maintains a small charge between electrodes until phase reversal occurs. A small current leak between electrodes would introduce a second time constant in the raw artifact signal indicative of the current flow between electrodes. This current leak would not be expected to scale linearly. The plots of the raw artifacts of SR-9 indicate that at the scaled magnitudes, less charge between electrodes is held at the end of 3 ms IPG for higher magnitude pulses. This indicates that the leak between electrodes is greater for higher magnitude stimuli.

After charge reversal, the assumption of linearity of the stimulus artifact holds for subject SR-9. An average of the final 15 points recorded 3 ms following delivery of the 2$^{nd}$ pulse (a time analogous to the 15 points recorded before initiation of the 2$^{nd}$ phase of the phase-separated stimulus), revealed scaling differences of less than 44 μV for each electrode combination and magnitude tested. Because the recordings from SR-3 indicate that the response to the 2$^{nd}$ phase of the phase-separated stimuli is the same as the response to the 1$^{st}$ phase of the stimulus with opposite polarity, the response to the 2$^{nd}$ phase only of the phase-separated stimuli was used as a measure of the isolated cathodic and anodic IEP responses for SR-9 with electrode combinations 3-4 and 2-3.

Figure 11 compares signals recorded without polarity reversals using the scaling technique for artifact reductions to signals using alternating polarity as a means of artifact reductions for SR-3 electrode combination 3-4. Single polarity recordings are shown on the left, and alternating polarity recordings are shown on the right. The responses to P1, P2, P3, and P4 are arranged from top to bottom in that order. For single polarity recordings, the anodic first

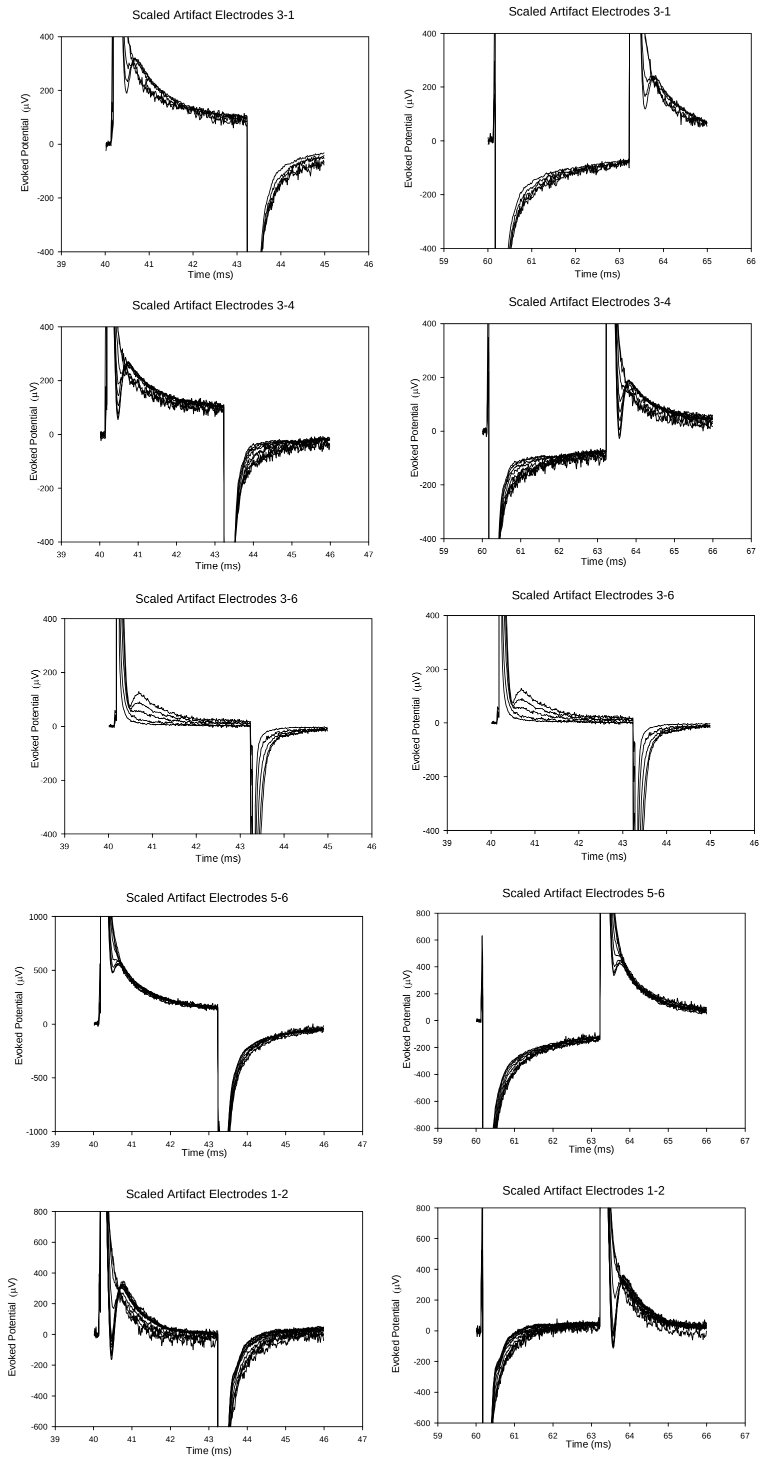


Figure 9: Raw evoked potential recordings from the electrode combinations shown for SR-3. Each potential has been scaled to the equivalent amplitude of the maximum current amplitude tested (see text). P3 responses are shown in the left-hand column, and P4 responses in the right-hand column.

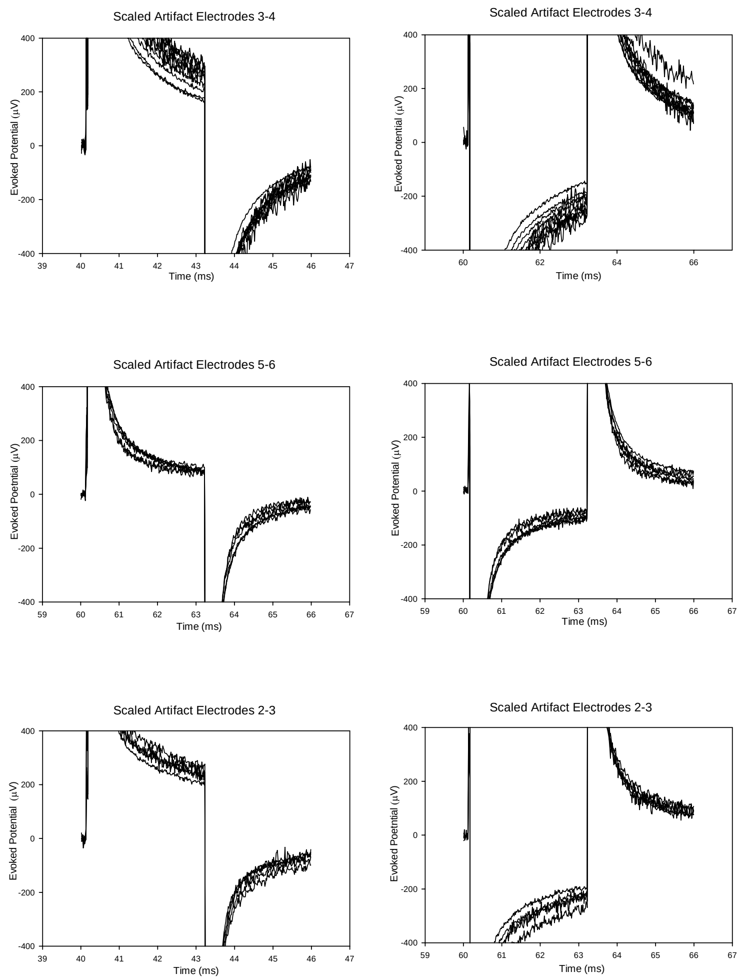


Figure 10: Raw evoked potential recordings from the electrode combinations shown for SR-9. Each potential has been scaled to the equivalent amplitude of the maximum current amplitude tested (see text). P3 responses are shown in the left-hand column, and P4 responses are shown in the right-hand column.

biphasic pulse without a pulse gap (a) has a larger amplitude N1 phase than the cathodic first biphasic pulse (b). The alternating polarity recordings produced by the two stimuli (e,f) are identical, as expected, and can be seen to represent an average of the phase-separated signals. The IEP recordings in response to phase-separated stimuli (c,d) both show a large N1 response for the isolated anodic stimulus and the absence of the N1 response with only a P2 response present for the isolated cathodic phase of the stimulus. The waveforms recorded in response to alternating stimuli (g,h) represent an average of the isolated anodic and cathodic waveforms demonstrating a lower-magnitude N1 waveform followed by a P2 waveform.

Figures 12-13 show recordings for the same conditions for SR-9. The response recorded from SR-9 is very different, and it should be noted that SR-9 has significantly lower speech reception scores than SR-3 [NU-6 monosyllabic word identification scores of 16% and 66%, respectively, with clinical CIS processors.] SR-9's responses to isolated single polarity stimuli show a broad negative response to anodic stimulation and a broad positive response to cathodic stimulation for electrode combinations 2-3 (Figure 12) and 3-4 (Figure 13).

## Discussion

The recordings show that the responses to the isolated cathodic and anodic stimuli differ. Therefore, the assumption of the alternating polarity method of artifact subtraction that only the artifact reverses with changing polarity while the biological response remains constant is not valid for single phase or phase-separated stimuli. The biological response to each phase of the stimulus differs, and the alternating polarity method of artifact reduction measures the average of the two responses.

For biphasic pulses without phase separation, the IEP recordings are similar indicating similar modes of stimulation and implying that both pulse polarities stimulate on the cathodic phase at a similar site. The anodic-first configuration, however, produces a larger N1 phase. Given the non-linear membrane recovery from depolarization and hyperpolarization, this result implies that anodic-first stimuli result in a lower response threshold than cathodic-first stimuli.

The isolated anodic stimulus produces a large N1 waveform followed by a P2 waveform in SR-3 although the P2 waveform is less obvious in SR-9. This response is very different from the isolated cathodic stimulus which produces a P2 waveform only. This result implies different modes and sites of stimulation. The one exception to this case, SR-9's combination 5-6 may result from an absence of viable cells in the vicinity of electrode 5. The small amplitude responses for all stimulus configurations may imply a distant site of excitation.

If the isolated cathodic stimulus produces an N1 waveform, the neural sources generating the response must respond quickly and with great synchrony so that the N1 waveform cannot be distinguished from the artifact. Another possibility is that the site of excitation might be sufficiently distant from the recording electrode so that only the P2 waveform is recorded. If a distant site of excitation is responsible for the lack of a recorded N1 phase in response to cathodic stimulation, this would imply that the isolated anodic stimulus results in a closer site of excitation. However, extracochlear evoked potentials recorded by Miller resulted in a P1 phase only for cathodic stimuli, implying that the anodic site of excitation was more distant from the

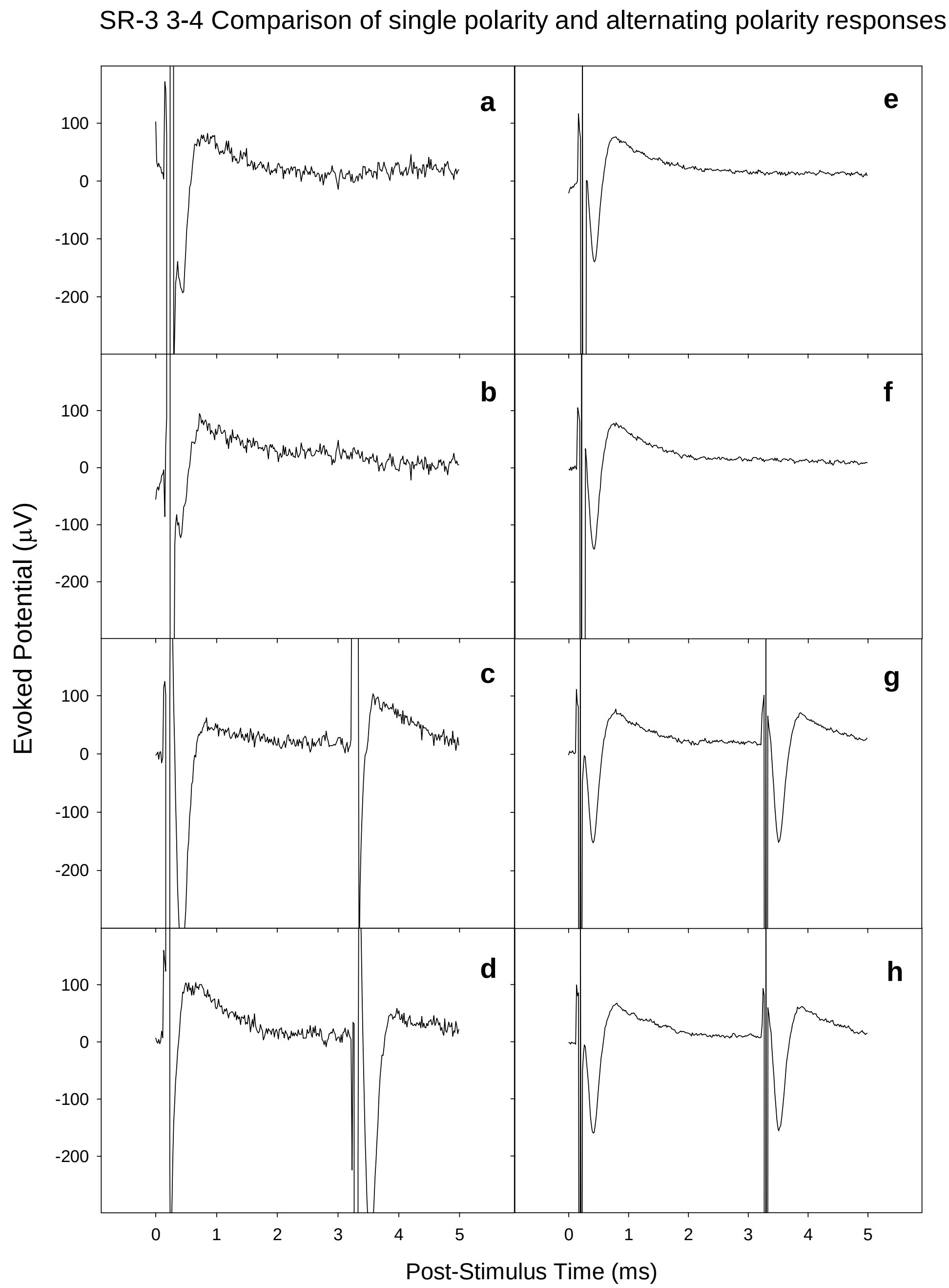


Fig. 11: IEPs recorded in response to single polarity stimuli using the scaling method of artifact subtraction (left column) are compared to IEPs with alternating polarity stimuli of the same amplitude and configuration (right column). Responses to P1, P2, P3, and P4 are shown from top to bottom. All stimuli were 900 μA.

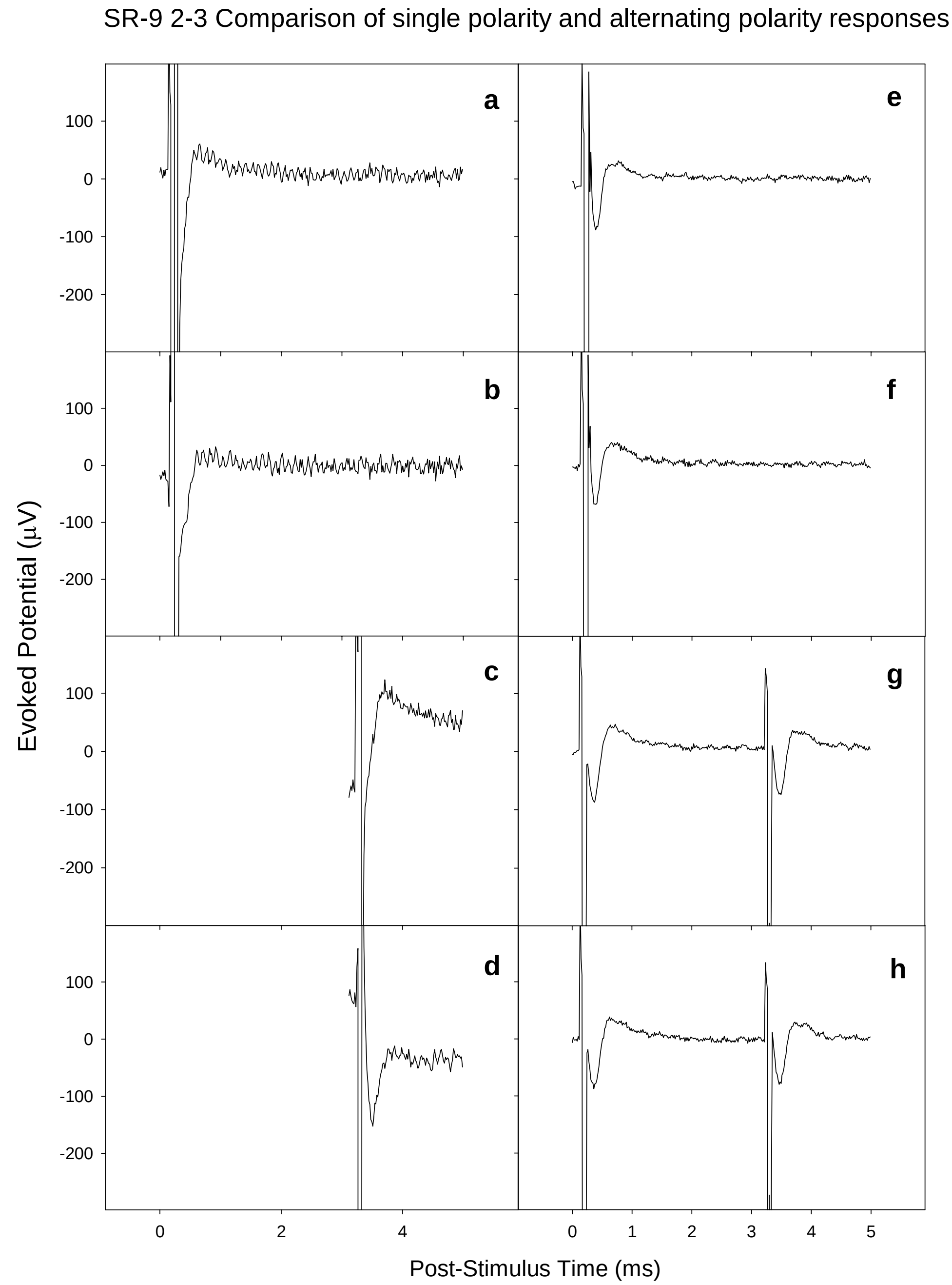


Fig. 12: IEPs recorded in response to single polarity stimuli using the scaling method of artifact subtraction (left column) are compared to IEPs with alternating polarity stimuli of the same amplitude and configuration (right column). Responses to the 2nd pulse only of biphasic pulses with a 3 ms IPG are shown as explained in the text. Responses to P1, P2, P3, and P4 are shown from top to bottom. All stimuli were 800 µA.

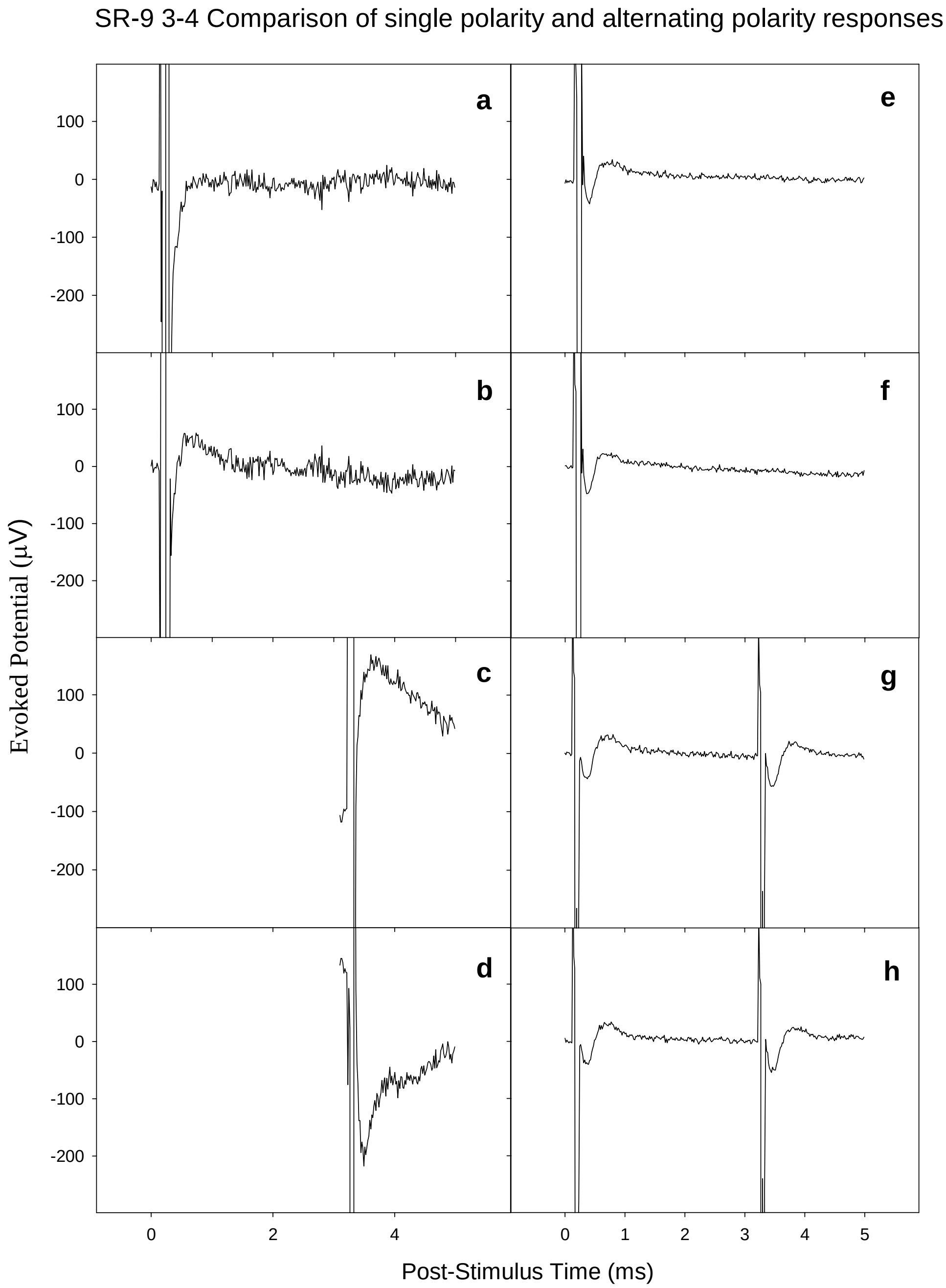


Fig. 13: IEPs recorded in response to single polarity stimuli using the scaling method of artifact subtraction (left column) are compared to IEPs with alternating polarity stimuli of the same amplitude and configuration (right column). Responses to the 2nd pulse only of biphasic pulses with a 3 ms IPG are shown as explained in the text. Responses to P1, P2, P3, and P4 are shown from top to bottom. All stimuli were 900 μA.

intracochlear electrodes than the cathodic site and close to the location of the extracochlear electrode. One possibility is that the large anodic response results from antidromic propagation. While a cathodic stimulus would be expected to depolarize the neurons at sites near the stimulating electrode preventing antidromic propagation in the direction of the stimulating electrode, the same is not true of an anodic stimulus. For a distant anodic stimulation site, it may be possible for antidromic propagation to ensue. The resulting excitation would propagate the peripheral end of the viable nerve fiber close the recording electrode producing a large evoked potential. However, if nerve fibers close to the recording fiber do not have viable nerve endings, antidromic propagation would not ensue. This may be the case with subject SR-9.

Clearly additional studies are needed to investigate some of the possible explanations of these preliminary data.

## III. References


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## IV. Plans for the next quarter

Among the activities planned for the next quarter are:

- Initial studies with Nucleus percutaneous subject NP-7, August 23-25
- Initial studies with Nucleus percutaneous subject NP-9, August 14-16
- A visit by Prof. Sung June Kim, September 27

## V. Acknowledgments

We thank volunteer research subjects ME-6, ME-20, and NP-8, who participated in studies conducted during this quarter, and subjects SR-3 and SR-9 who participated in earlier studies described in this report.

## Appendix 1: Announcements and Summary of reporting activity for this quarter

We are pleased to note that Blake Wilson was named as the Special Guest at the recent *Eighth International Cochlear Implant Conference*, held in Indianapolis, IN, May 10-13.

Robert Wolford will be leaving the RTI team in early August 2004, to pursue a Ph.D. degree at the University of North Carolina, Chapel Hill, full time. He has contributed mightily to this and prior projects in the "speech processors" series at RTI. We will miss him and wish him all the best in his new endeavor.

### Publications

- Wilson BS: Engineering design of cochlear implant systems. In *Auditory Prostheses: Cochlear Implants and Beyond*, edited by F-G Zeng, AN Popper and RR Fay, Springer-Verlag, New York, 2004, pp 14-52. (This book is volume 20 in the highly acclaimed *Springer Handbook of Auditory Research*.)

### Invited Presentations

- Wilson BS, Schatzer R, Wolford RD, Sun X: Two new directions in implant design. *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004. (Special Guest Address)
- Wilson BS, Wolford RD, Lawson DT, Schatzer R, Brill S, *et al.*: Combined electric-acoustic stimulation (EAS) of the auditory system. *Med-El Satellite Meeting*, *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004. (Honorary Speaker presentation)
- Wilson BS, Wolford RD, Lawson DT, Schatzer R, Brill S, *et al.*: Combined electric-acoustic stimulation (EAS) of the auditory system. *Med-El Satellite Meeting, Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004. (Surgeon's Workshop presentation)

### Chaired Session

- Wilson BS, Talavage TM (Co-Chairs): Session 2C. *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004.

# Appendix A:  Additional Figures

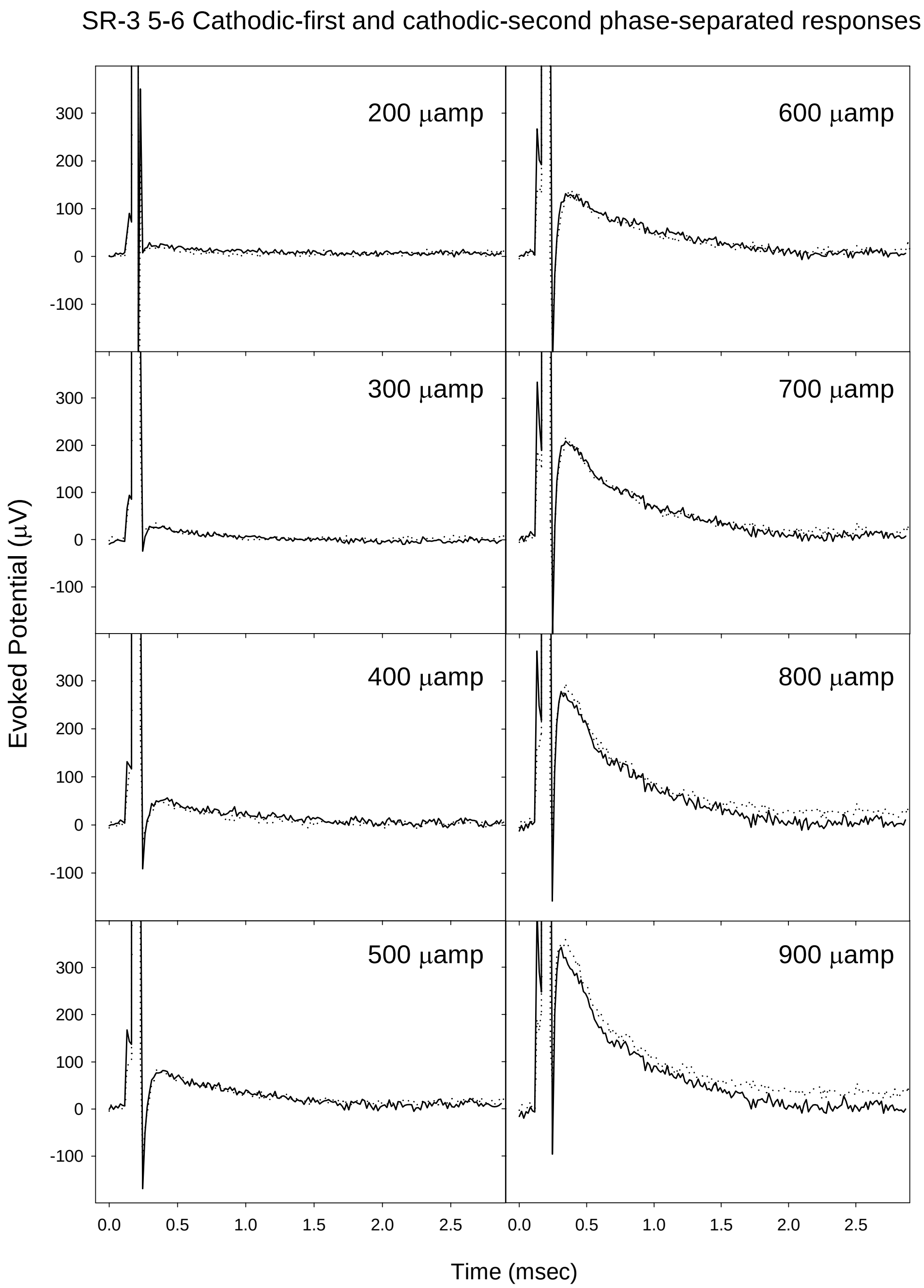


Fig. A-1: IEPs recorded in response to the intial cathodic phase of a cathodic-leading biphasic pulse (dashed line) with a 3 ms IPG, and the final cathodic phase of an anodic-leading biphasic pulse with a 3 ms IPG (solid line).  Stimulus artifact was reduced using the scaling method of artifact subtraction.

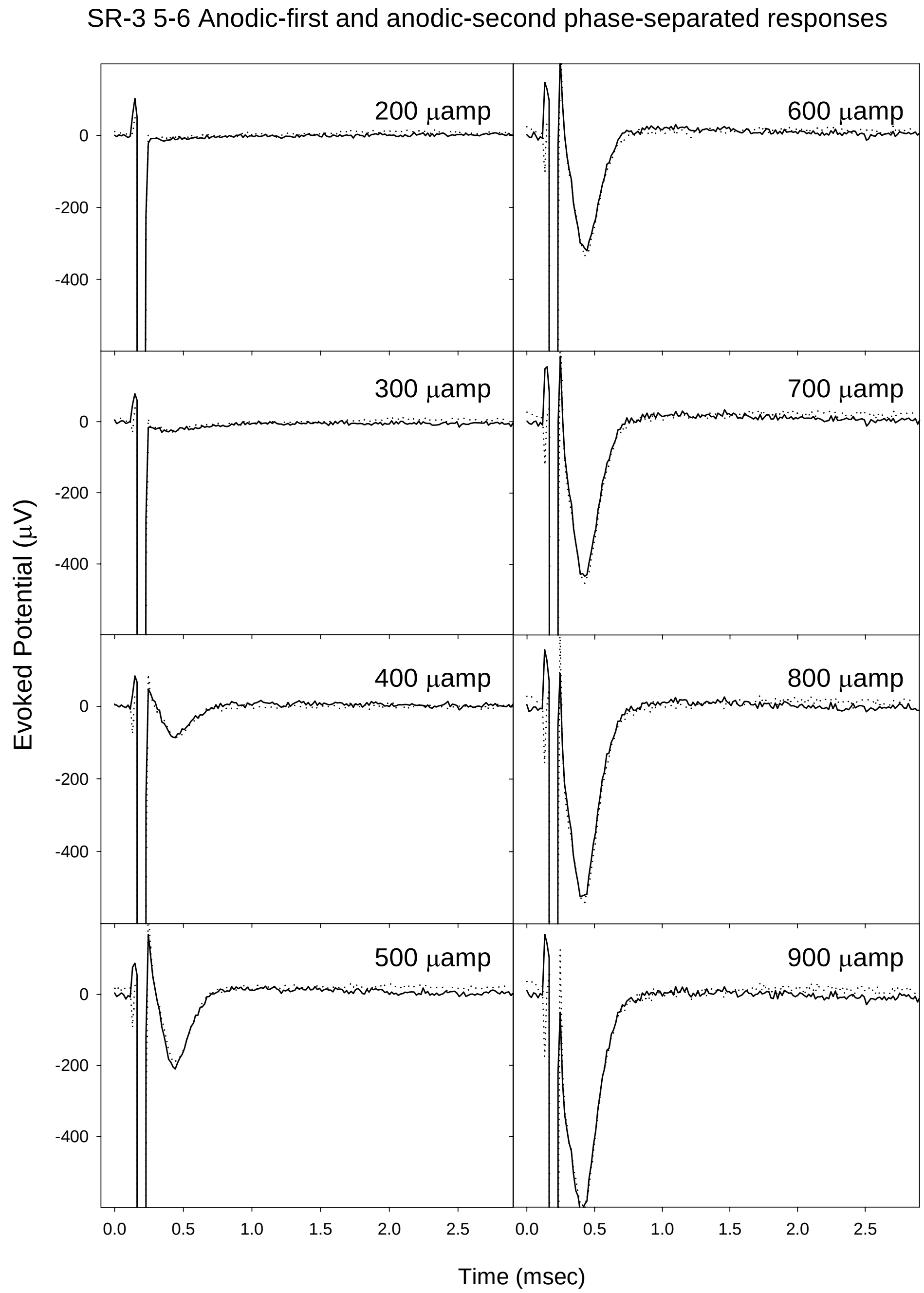


Fig. A-2: IEPs recorded in response to the intial anodic phase of an anodic-leading biphasic pulse (solid line) with a 3 ms IPG, and the final anodic phase of an cathodic-leading biphasic pulse with a 3 ms IPG (dashed line). Stimulus artifact was reduced using the scaling method of artifact subtraction.

SR-3 1-2 Cathodic-first and cathodic-second phase-separated responses

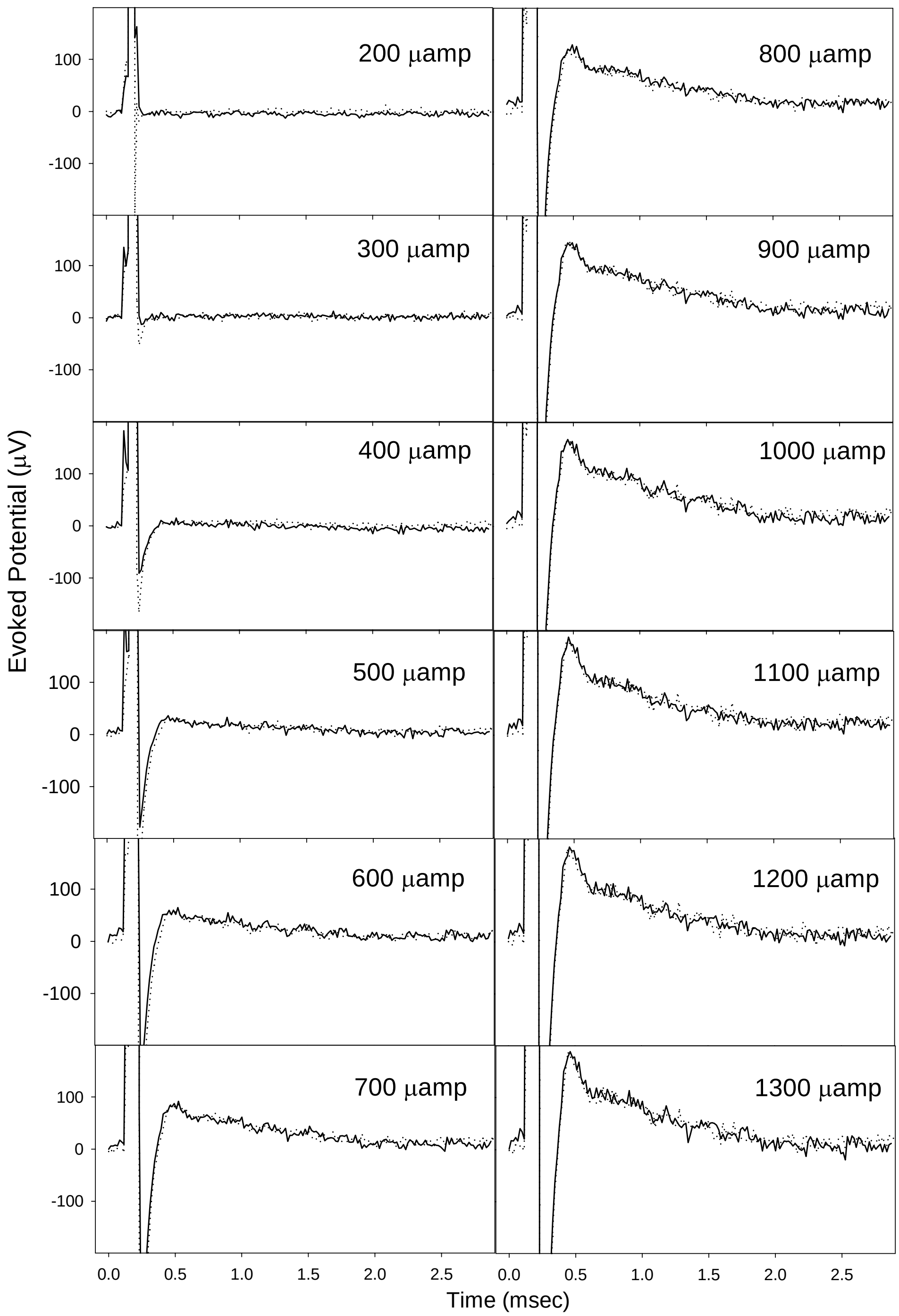


Fig. A-3: IEPs recorded in response to the intial cathodic phase of a cathodic-leading biphasic pulse (dashed line) with a 3 ms IPG, and the final cathodic phase of an anodic-leading biphasic pulse with a 3 ms IPG (solid line). Stimulus artifact was reduced using the scaling method of artifact subtraction.

SR-3 1-2 Anodic-first and anodic-second phase-separated responses

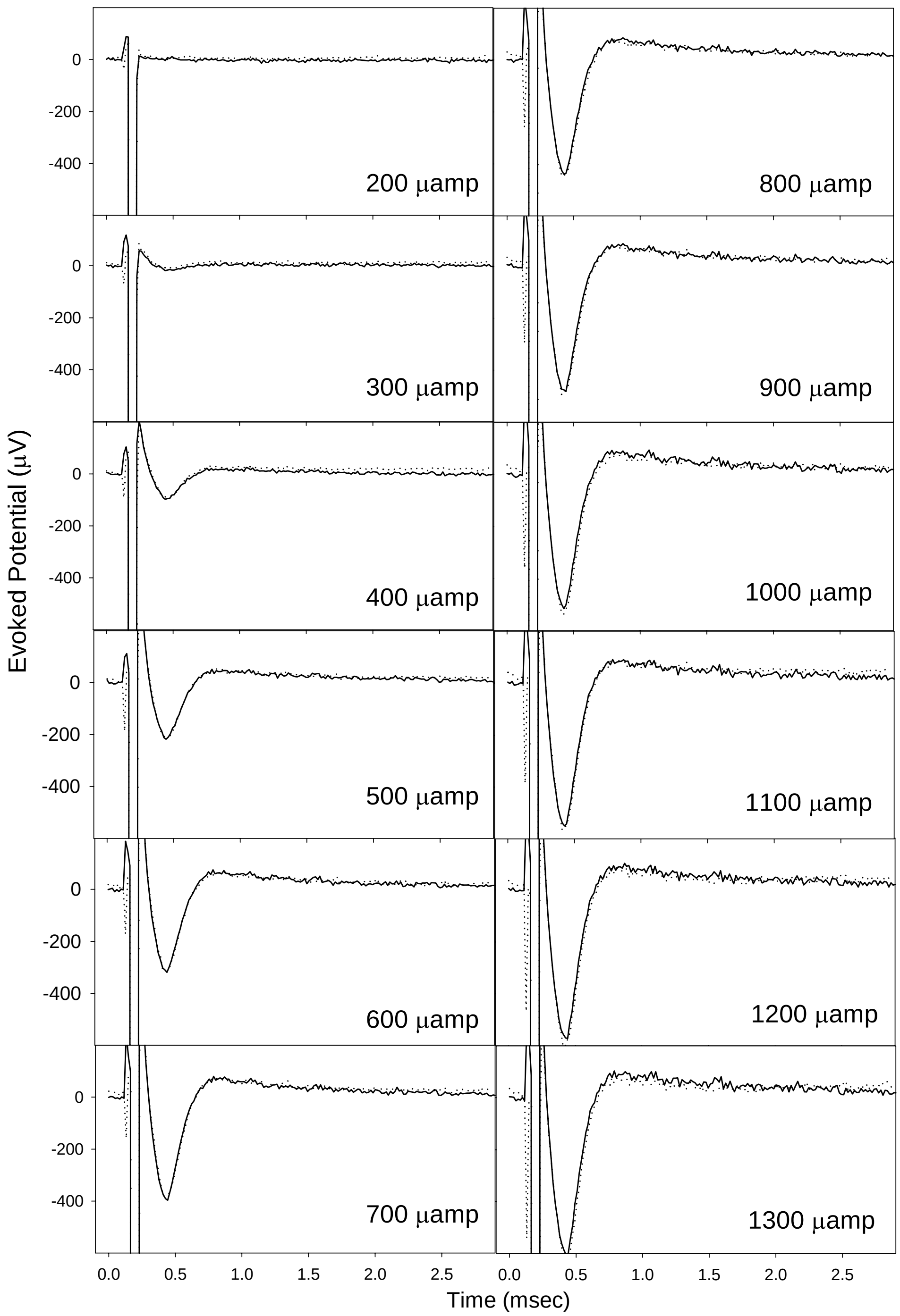


Fig. A-4: IEPs recorded in response to the intial anodic phase of an anodic-leading biphasic pulse (dashed line) with a 3 ms IPG, and the final anodic phase of an cathodic-leading biphasic pulse with a 3 ms IPG (solid line). Stimulus artifact was reduced using the scaling method of artifact subtraction.