Eleventh Quarterly Progress Report

February 1 through April 30, 1995

NIH Contract N01-DC-2-2401

Speech Processors for Auditory Prostheses

Prepared by

Blake S. Wilson, Charles C. Finley, Dewey T. Lawson and Mariangeli Zerbi

Center for Auditory Prosthesis Research
Research Triangle Institute
Research Triangle Park, NC 27709

CONTENTS

I. Introduction

The purpose of this project is to design and evaluate speech processors for implantable auditory prostheses. Ideally, the processors will extract (or preserve) from speech those parameters that are essential for intelligibility and then appropriately represent those parameters for electrical stimulation of the auditory nerve or central auditory structures. Work in the present quarter included the following:

1. A meeting at RTI with Jim Patrick, Ron West and Jim Heller, to discuss progress and plans for studies involving patients with percutaneous access to the Nucleus electrode array (Wilson and Lawson, February 2).
2. Presentation of project results in one invited lecture and one poster at the annual *Midwinter Meeting of the Association for Research in Otolaryngology* (Wilson and Finley, February 5-9).
3. A meeting in Boston with Don Eddington, Marco Pelizzone, Jacques François and others, to discuss progress and plans for the continued joint development of a highly flexible and portable speech processor system (Zerbi, February 12-15).
4. Presentation of project results at Otolaryngology Grand Rounds, Duke University Medical Center (Lawson, February 15).
5. Continued studies with Nucleus percutaneous subjects NP2 (January 30 to February 10) and NP1 (March 13-24), including for each of the subjects repeated measures with the SPEAK strategy, detailed evaluation of CIS processors using more than six channels, and measures of intracochlear evoked potentials. Studies with NP1 also included electrophysiological measures of forward masking for 200 ms trains of pulses, with various pulse amplitudes and pulse rates.
6. Continued studies with Ineraid subject SR2, including electrophysiological and psychophysical measures of forward masking for a wide range of maskers with various burst durations, pulse amplitudes, and pulse rates (February 20 to March 6).
7. A trip to the University of Innsbruck, at the invitation of the University, to participate in research there on the fitting and evaluation of CIS processors (Lawson, March 5-10).
8. Continued studies with Ineraid subject SR3, including recordings of intracochlear evoked potentials for a wide variety of stimuli, electrophysiological and psychophysical measures of forward masking, and initiation of chronic studies with a portable CIS processor, as implemented in hardware developed at the University of Innsbruck with our help (April 3-13).
9. Presentation of project results at the *IIIrd International Congress on Cochlear Implant*, held in Paris, France (Wilson, April 27-29).
10. Continued analysis of speech reception and evoked potential data from prior studies, and continued preparation of manuscripts for publication.

In this report we describe recordings of intracochlear evoked potentials for sustained electrical stimuli, including long bursts of identical pulses, long bursts of sinusoidally amplitude modulated (SAM) pulse trains, and the pulsatile outputs of a single-channel speech processor. Results from other studies and activities, as indicated in the list above, will be presented in future reports.

II. Recordings of Intracochlear Evoked Potentials for Sustained Electrical Stimuli

As first described in the Seventh Quarterly Progress Report for this project, we have begun a series of studies to record responses of the auditory nerve to intracochlear electrical stimulation. Studies have been conducted with implant patients having percutaneous connectors, i.e., patients with either the Ineraid device or an experimental version of the Nucleus device that includes a percutaneous connector. Recordings are made using unstimulated electrodes in the implant array. An example is presented in Figure 1 for trains of identical pulses presented to electrode 3 in the implant array of Ineraid subject SR2. Potentials following the pulses were recorded differentially between intracochlear electrode 4 and the ipsilateral mastoid. Body potential was measured with a reference electrode at the wrist. Additional details on the recording technique are presented in the caption for Figure 1 and in QPR 7.

In prior studies we recorded responses of human auditory nerve to relatively short bursts of pulses and sinusoidally amplitude modulated (SAM) pulse trains (see Figures 11, 13, and 15 through 20 in QPR 7). The maximum burst duration was 200 ms. We now have extended our set of stimuli to include burst durations of approximately one second for pulse trains and SAM pulse trains. We expected that recordings of responses to such sustained stimuli might provide further information on the time course of accommodation or fatigue in the nerve. In addition, we wanted to know whether the neural representation of the temporal fine structure in these stimuli might change over time, e.g., whether the alternating pattern of response from pulse to pulse observed before for a 1016 pps stimulus might be diminished or absent beyond 200 ms.

An additional purpose of the present studies was to determine effects of modulation depth on the neural representation of SAM pulse trains. Recordings were made for the depths of 100, 80 and 20 percent, and for the modulation frequencies of 101.6 and 406.4 Hz. The carrier rate was 1016 pps for each of the recordings.

Finally, we wanted to know how well patterns of response in the auditory nerve might reflect patterns of pulse amplitudes in the outputs of a single-channel speech processor. We expected that any demonstrated distortions in the neural representations might help us understand the limitations of current processing strategies and perhaps provide insights into ways the current strategies might be improved.

Responses to Pulse Trains and SAM Pulse Trains

Patterns of responses to pulse trains and SAM pulse trains are presented in Figures 2 through 4 for Ineraid subject SR2 and in Figures 5 through 7 for Ineraid subject SR3. The first in each set of figures shows the normalized magnitudes of the evoked potentials (measured as the difference in amplitudes of the first negative peak and the first positive peak in the EP waveforms, see QPR 7 for additional details) following each stimulus pulse in the entire 1000 ms record. The second figure in each set shows EP magnitudes for the first 100 ms of each record, and the third figure in each set shows EP magnitudes for the final 100 ms. In addition to EP magnitudes, normalized amplitudes of the stimulus pulses are indicated in the second and third figures of each set.

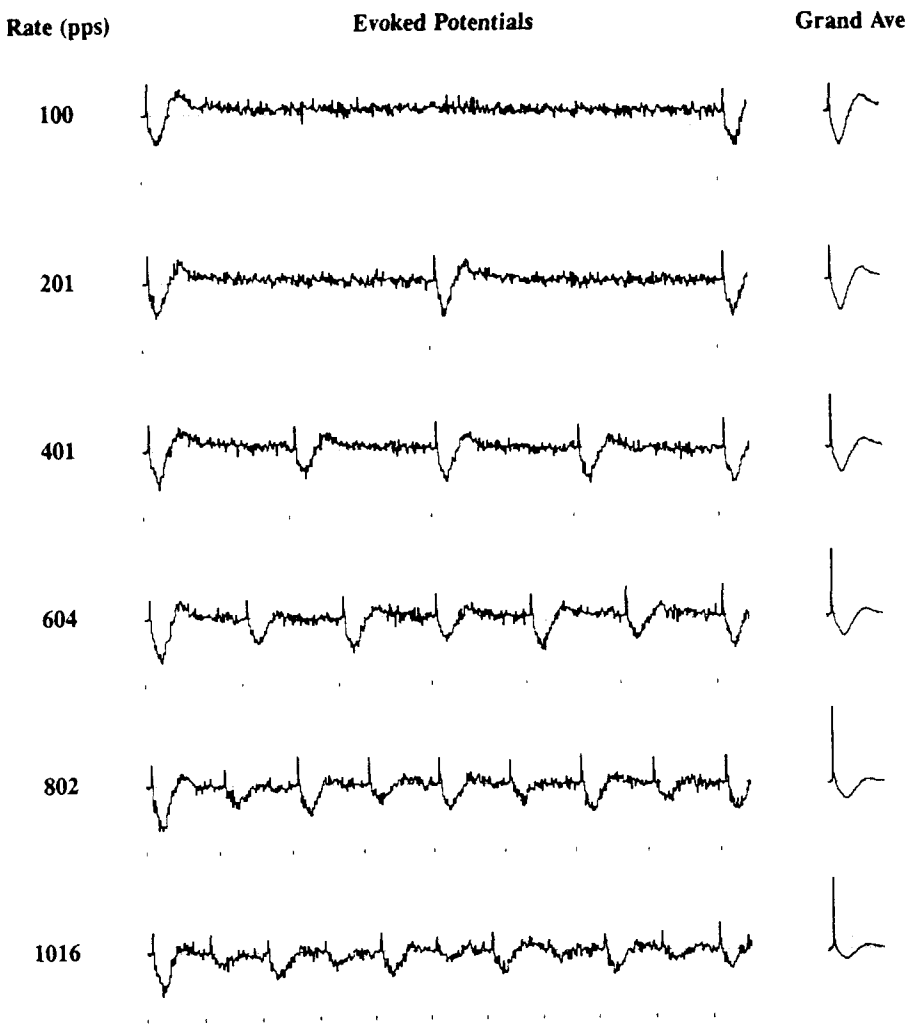

Figure 1. Recordings of intracochlear evoked potentials for Ineraid subject SR2. Stimuli included 16.4 μs/phase pulses presented at the indicated rates to electrode 3 in the Ineraid array (the array has 6 intracochlear electrodes, with electrode 1 the most apical). Pulse amplitude was 750 μA for all illustrated conditions. This amplitude produced a most comfortable loudness (MCL) percept for the pulse rate of 1016/s. Lower pulse rates at the same amplitude produced lower loudnesses. The times of pulse presentations are indicated in the figure with the short vertical lines beneath each EP trace. Potentials were recorded differentially between intracochlear electrode 4 and the ipsilateral mastoid. Body potential was measured with a reference electrode at the wrist. A blanker circuit was used during pulse presentations to reduce the magnitude of pulse artifacts in the recordings. In addition, responses from 200 sweeps of pulses with the positive phase leading were added to responses from 200 sweeps of pulses with the negative phase leading. As illustrated, these two procedures reduced pulse artifacts to a low level (residual artifacts are seen in the "spikes" preceding each EP). The average of EPs following each pulse for a given condition is shown in the right column, under the heading of "Grand Ave." The horizontal dotted lines in the EP columns indicate zero potential. Note that EPs fail to follow pulses with equal magnitudes for rates of stimulation above 201 pps.

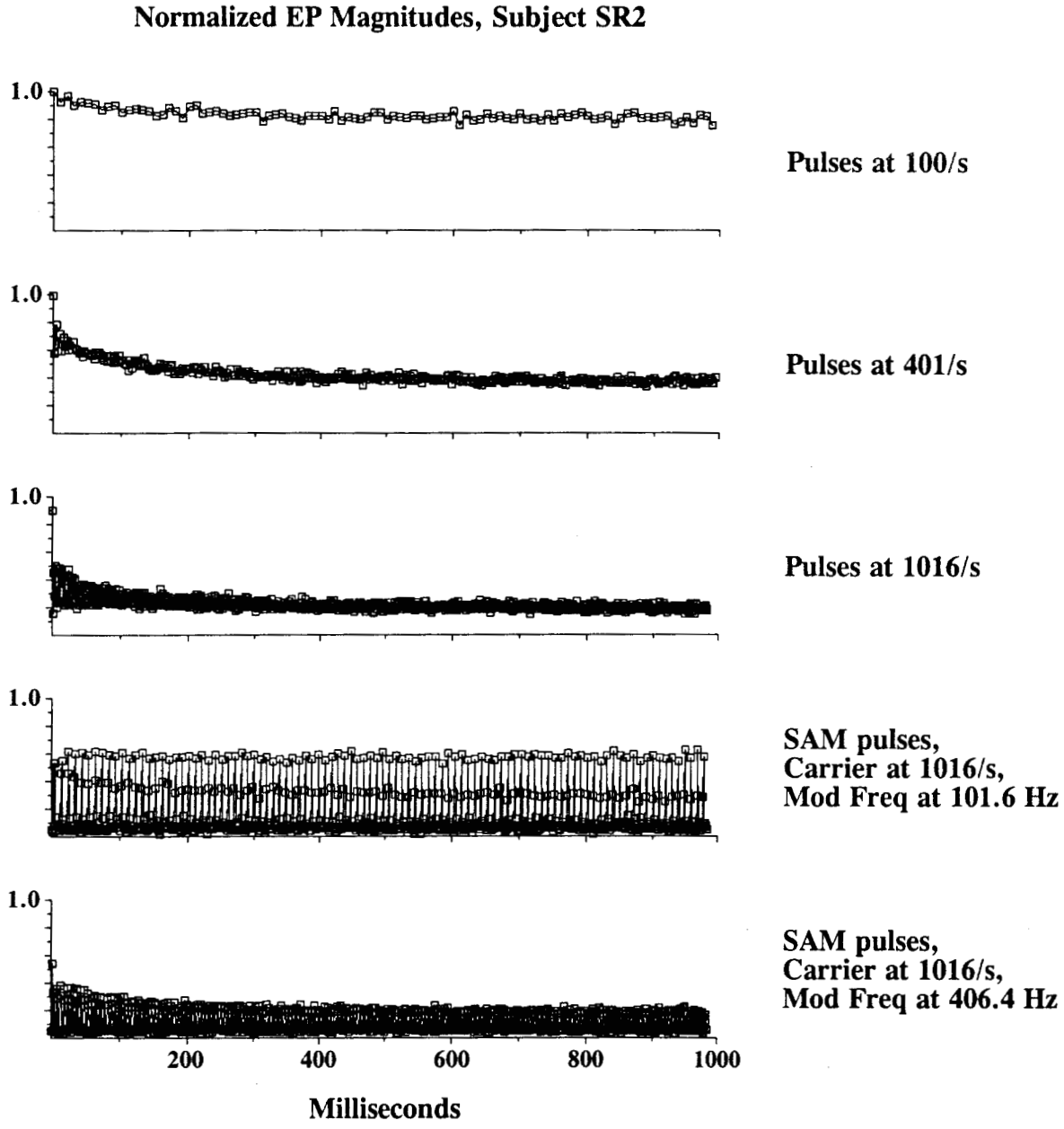

Figure 2. Normalized magnitudes of evoked potentials for Ineraid subject SR2. Stimuli were delivered to electrode 3 of the implant with reference to a remote electrode in the temporalis muscle. Potentials were recorded differentially between electrode 4 and an external electrode at the ipsilateral mastoid. The top three panels show EP magnitudes for trains of identical pulses with the indicated rates of pulse presentations within the trains. The bottom two panels show EP magnitudes for sinusoidally amplitude modulated (SAM) pulse trains with the indicated carrier rate and modulation frequencies. The level of the carrier, and the amplitude of the pulses in the trains of identical pulses, was 290 μA. The duration of all pulses was 32.8 μs/phase. The condition involving the presentation of identical pulses at 1016/s produced a most comfortable loudness (MCL) percept. Lower loudnesses were produced for all other conditions. The maximum EP magnitude across these five conditions for this subject was 90.2 μV.

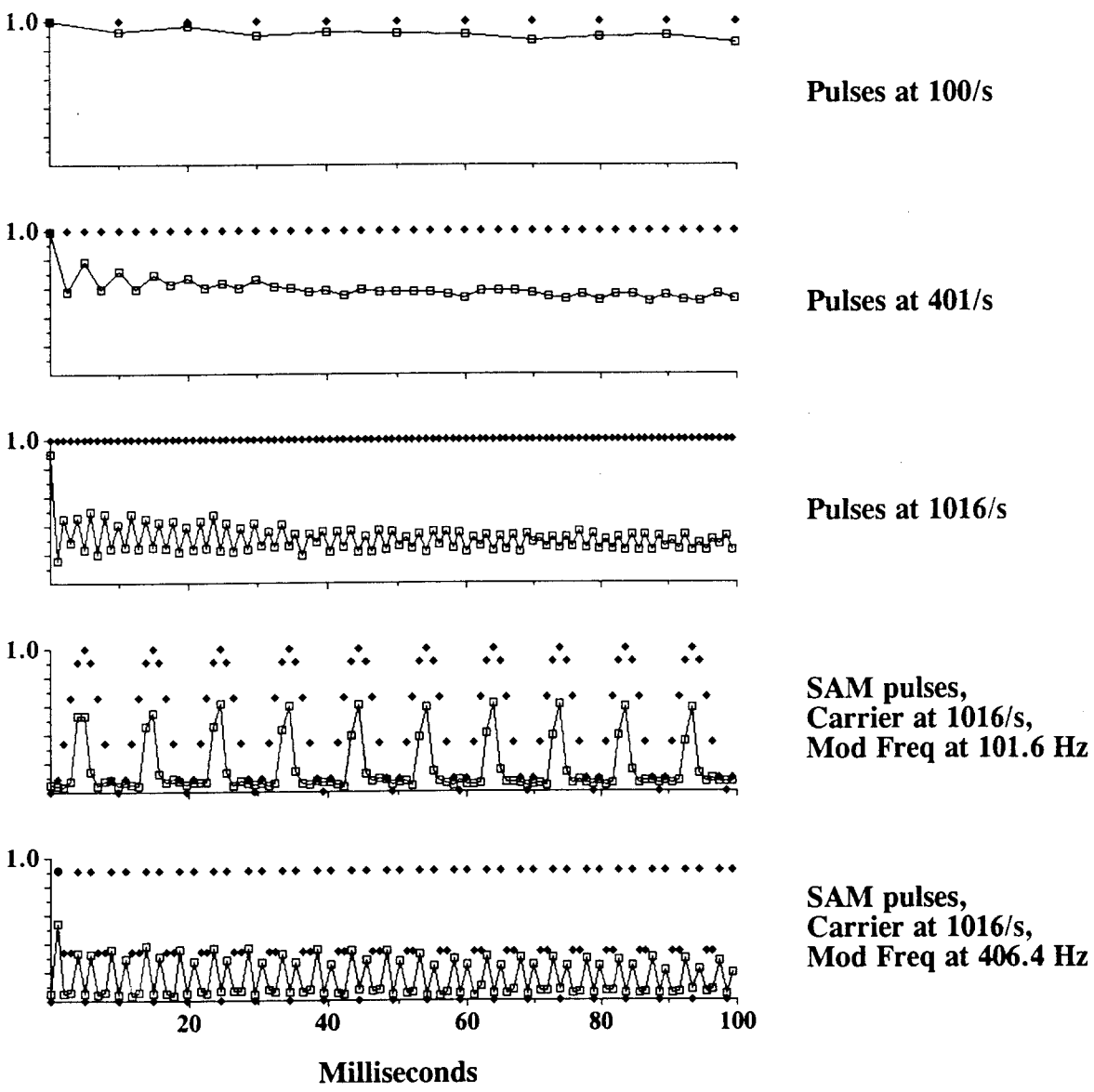

Figure 3. First 100 ms of the records shown in Figure 2. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

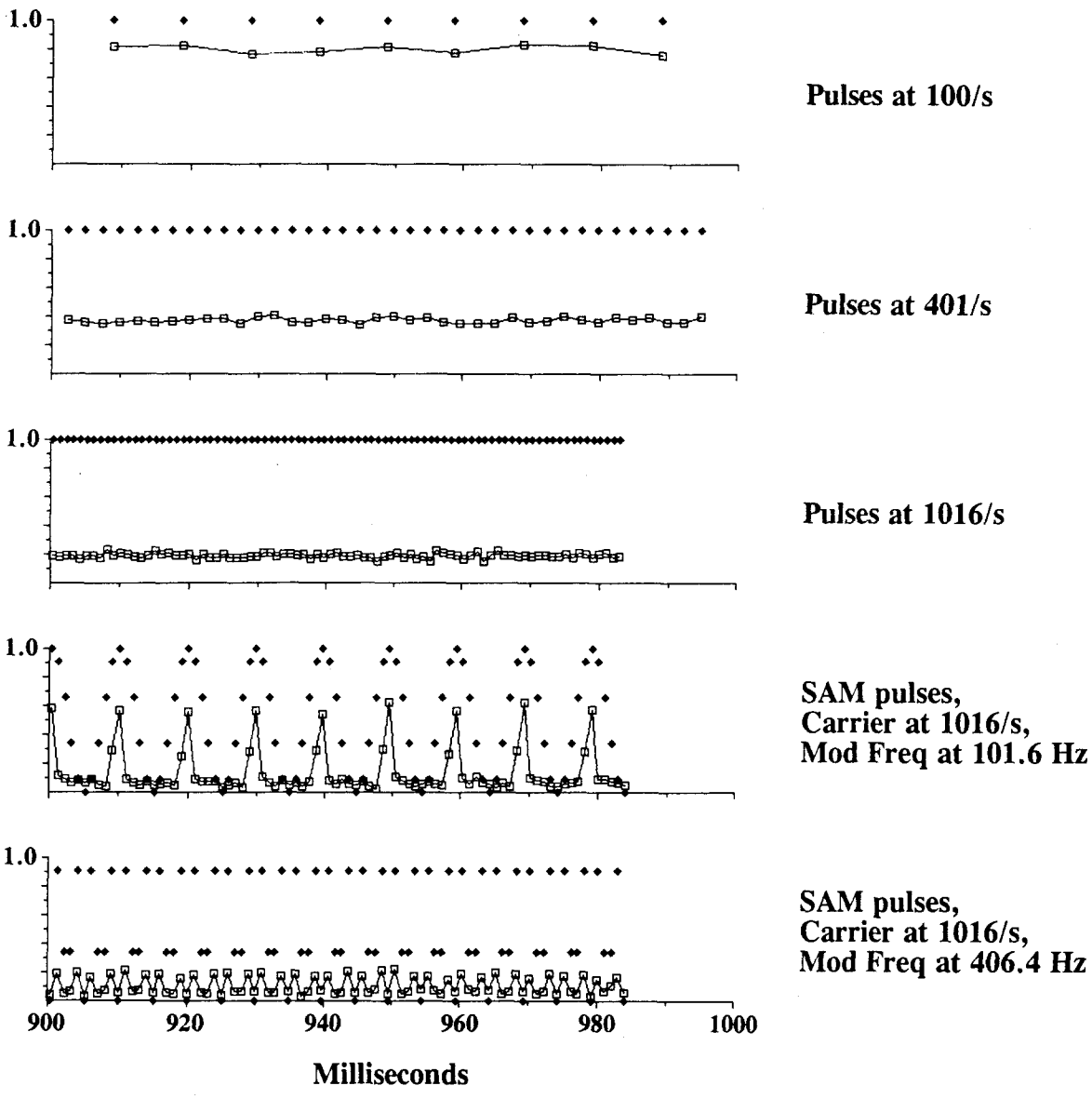

Figure 4. Final 100 ms of the records shown in Figure 2. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

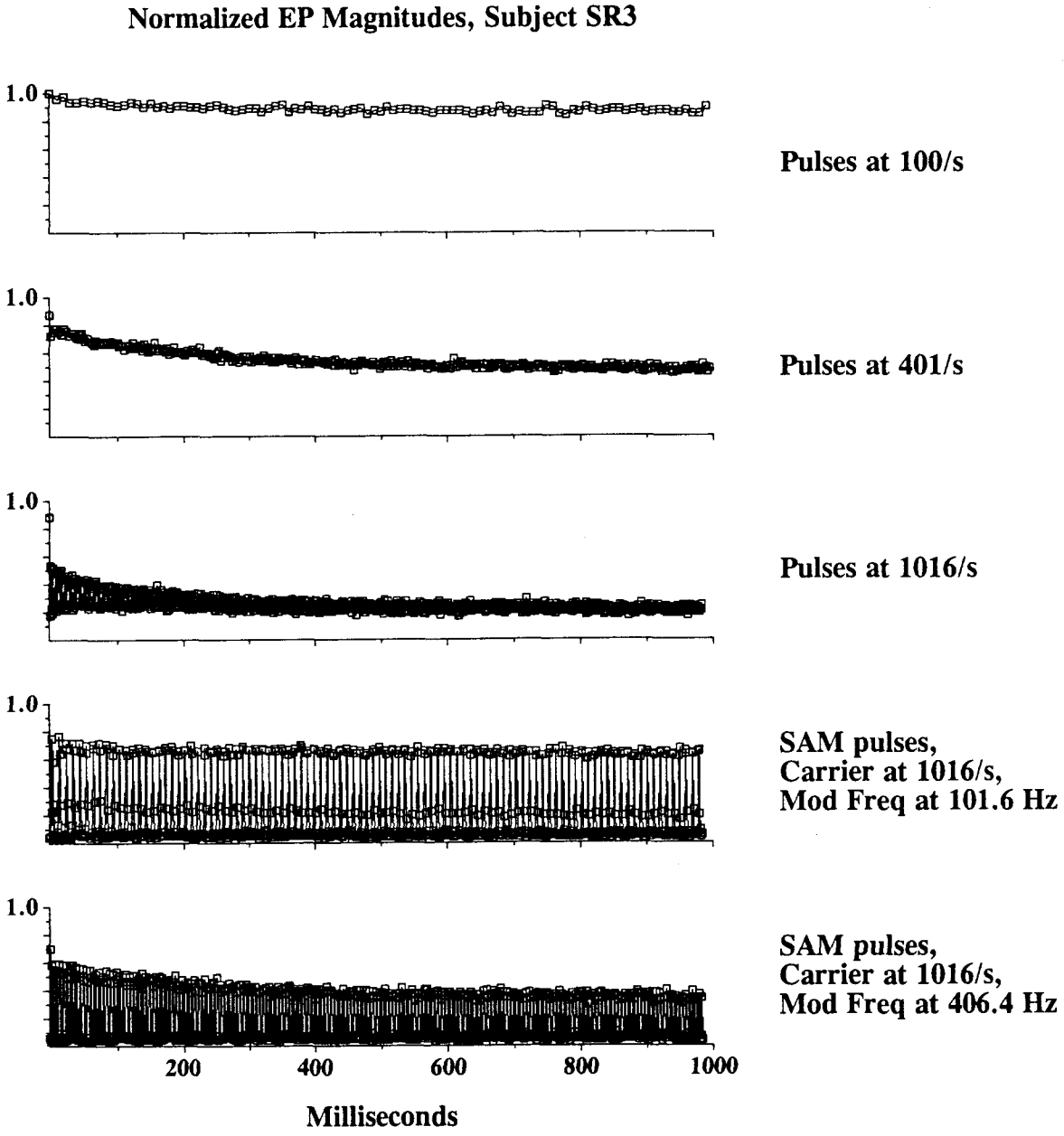

Figure 5. Normalized magnitudes of evoked potentials for Ineraid subject SR3. Stimuli were delivered to electrode 3 of the implant with reference to a remote electrode in the temporalis muscle. Potentials were recorded differentially between electrode 4 and an external electrode at the ipsilateral mastoid. The top three panels show EP magnitudes for trains of identical pulses with the indicated rates of pulse presentations within the trains. The bottom two panels show EP magnitudes for sinusoidally amplitude modulated (SAM) pulse trains with the indicated carrier rate and modulation frequencies. The level of the carrier, and the amplitude of the pulses in the trains of identical pulses, was 520 μA. The duration of all pulses was 32.8 μs/phase. The condition involving the presentation of identical pulses at 1016/s produced a most comfortable loudness (MCL) percept. Lower loudnesses were produced for all other conditions. The maximum EP magnitude across these five conditions for this subject was 104.3 μV.

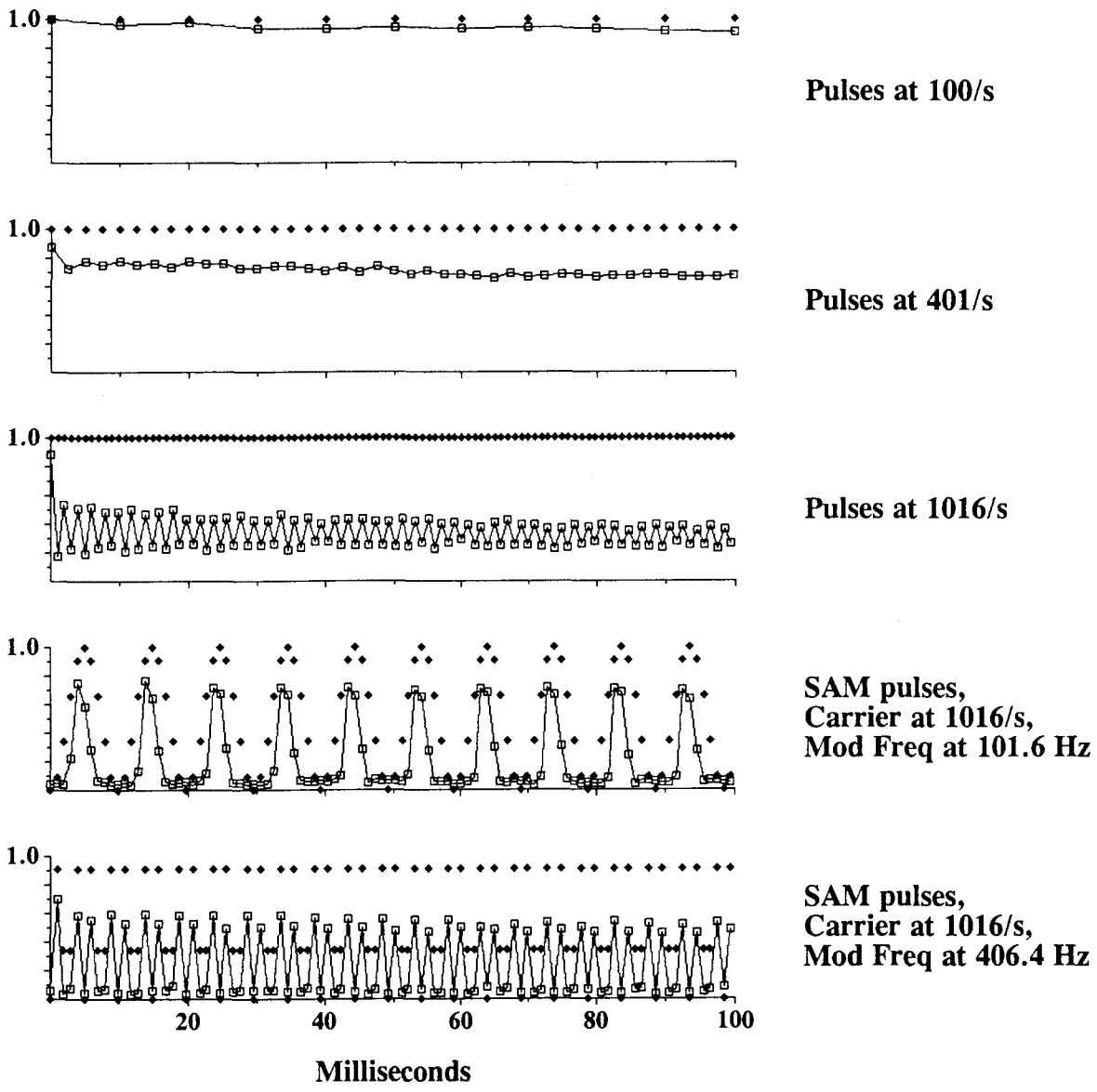

Figure 6. First 100 ms of the records shown in Figure 6. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

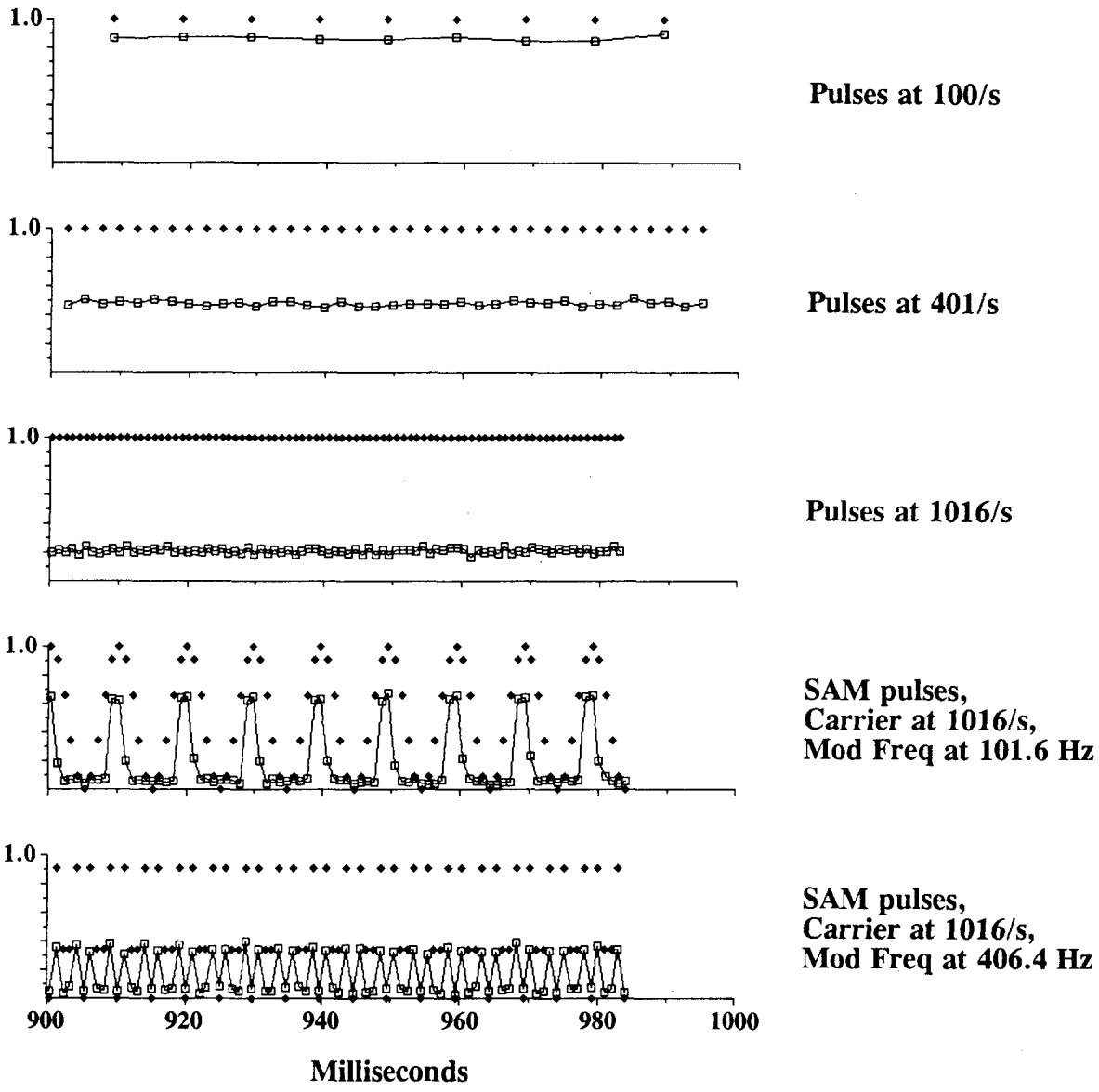

Figure 7. Final 100 ms of the records shown in Figure 6. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

For reference, both subjects enjoy high levels of speech recognition with their implant systems. Subject SR2 obtains percent correct NU-6 word scores in the high 90s for a variety of *continuous interleaved sampling* (CIS) processors used in conjunction with his Ineraid electrode array, and subject SR3 obtains scores in the mid to high 50s for that test, again with CIS processors used in conjunction with the Ineraid electrode array.

Responses to trains of pulses are broadly similar for the two subjects. Both Figures 2 and 5 show decrements in response over time for these stimuli. This is most evident for the 401 pps stimulus, where the magnitudes of EPs following each pulse continue to decline out to about 300 or 400 ms for both subjects. The magnitude of the decrement is somewhat greater for subject SR2.

Although small, decrements in response over time also can be observed for the 100 pps stimulus. This is most easily seen in comparing the upper panels of Figures 3 and 4 for subject SR2, and in comparing the upper panels of Figures 6 and 7 for subject SR3. As with the 401 pps stimulus, the magnitude of the decrement is somewhat greater for subject SR2. The time course of reductions in EP magnitudes appears to be similar for the 100 and 401 pps stimuli for both subjects, although the very small reductions for subject SR3 make this judgment difficult.

As before, an alternating pattern of response is observed for the 1016 pps stimulus, for both subjects. The difference between the relatively large EP magnitudes for odd-numbered pulses and the relatively small EP magnitudes for even-numbered pulses declines over time. Ultimately, the EP magnitudes for odd- and even-numbered pulses become indistinguishable, as may be seen in the middle panel of Figure 4 for subject SR2 and in the middle panel of Figure 7 for subject SR3. The average of EP magnitudes for sequential 1016 pps pulses also declines over time, as shown in Figures 2 to 4 for SR2 and in Figures 5 to 7 for SR3. Most or all of the decrements appear to occur within the first 300 to 400 ms, as with the 100 and 401 pps stimuli.

An alternating pattern of response also is observed for the initial pulses in the 401 pps stimulus for both subjects. This is most evident for subject SR2, whose responses alternate for the first eight to ten pulses, as shown in Figure 3. There is, perhaps, a hint of the same effect for subject SR3 (Figure 6) and in both subjects' records for the 100 pps stimuli (Figures 3 and 6). In the latter case, however, the differences in EP magnitudes across the first four pulses approximate the level of noise in the recordings, so the conclusion that an alternating pattern is present for the 100 pps stimuli must remain tentative.

Patterns of responses to SAM pulse trains reflect to some extent the modulation of pulse amplitudes. For the 101.6 Hz modulation, responses for both subjects are in synchrony with the periodicity of the modulation waveform. A detectable response is observed for the fifth stimulus pulse in each cycle of 10 pulses for both subjects. The normalized amplitude of this pulse is 0.905. A similar or larger response is observed for the sixth pulse in each cycle for both subjects. The normalized amplitude of this pulse is 1.0. A diminished or no detectable response is observed for the subsequent, lower amplitude pulses in each cycle.

Details in the patterns of response change over the first several cycles for both subjects. A just

detectable response is elicited by the fourth pulse (normalized amplitude of 0.655) in the first cycle for subject SR2 (Figure 3) and a relatively large response is elicited by that pulse in the first cycle for subject SR3 (Figure 6). Detectable responses to the fourth pulse in the subsequent three cycles are also present in the record for SR3.

In addition, the responses to pulses five and six change somewhat over the first several cycles for both subjects. For SR2 the EP magnitudes are quite similar for those pulses in the first cycle. In subsequent cycles the response to pulse five is progressively diminished over the first 200 ms of the stimulus while the response to pulse six is slightly augmented for cycles two and three and then maintained for the remainder of the record (Figures 3 and 4). For SR3 the response to pulse five is greater than the response to pulse six for the first two cycles. In all subsequent cycles the responses to the two pulses are more similar (Figures 6 and 7).

Although minor variations are observed in responses from cycle to cycle, the peak magnitudes of EPs across cycles are approximately uniform for the full duration of the 101.6 Hz SAM stimulus, for both subjects.

Patterns of response for SAM pulse trains with 406.4 Hz modulation also are similar for the two subjects. A relatively large response is elicited by stimulus pulse two, and little or no response by pulses three and four, for both subjects (bottom panels of Figures 3 and 6). Pulse two is the first non-zero pulse, with a normalized amplitude of 0.905. Pulses three and four have normalized amplitudes of 0.345. This pattern of pulse amplitudes -- zero, 0.905, 0.345 and 0.345 -- is repeated across cycles for 406.4 Hz modulation of a 1016 pps carrier. EP magnitudes for pulse four appear to be somewhat higher than those for pulse three for cycles near the beginning of the record for subject SR3 (Figure 6). This suggests that the normalized amplitude of 0.345 may be just sufficient to elicit a detectable response for this subject when presented after pulses with normalized amplitudes of 0.905 and 0.345. Possible mechanisms underlying the response to the second 0.345 pulse include (a) recovery or partial recovery from prior stimulation with the 0.905 pulse and/or (b) temporal summation effects across the two 0.345 pulses.

Peak magnitudes of EPs decline over time for both subjects with 406.4 Hz modulation condition. The response to pulse two is greater than the response to all subsequent pulses with a normalized amplitude of 0.905. Also, the responses to those subsequent pulses exhibit a slow decrease in magnitude thereafter. The time course of this slow component appears to be similar to that of responses to identical pulses presented at 401/s, quite near the modulation frequency of the present condition. However, the magnitude of the decrement appears to be somewhat less with SAM pulse trains than with identical pulses presented at the modulation frequency (compare second and fifth panels in Figure 2 for subject SR2 and those panels in Figure 5 for subject SR3).

The overall response with 406.4 Hz modulation is somewhat lower than the overall response with 101.6 Hz modulation, for both subjects. This may reflect the difference in the peak amplitude of stimulus pulses for the two conditions. For the 406.4 Hz condition that amplitude was 0.905, whereas for the 101.6 Hz condition it was 1.0.

In general, responses to SAM pulse trains reflect features of the modulation waveform. Unlike responses to identical pulses at the carrier rate, the responses to SAM pulse trains are sustained at a relatively constant level over one second of stimulation with the 101.6 Hz modulation frequency. At the higher modulation frequency a slow decrement is observed in the response over time, similar to but not quite as great as the decrement observed for identical pulses presented at the modulation frequency.

Effects of Modulation Depth for SAM Pulse Trains

Patterns of responses to SAM pulse trains with various depths of modulation are shown in Figures 8 through 10 for subject SR2 and in Figures 11 through 13 for subject SR3. The top three panels in each of these figures show responses for 101.6 Hz modulation of a 1016 pps carrier, and the bottom three panels show responses for 406.4 Hz modulation of the same carrier. Depths of modulation include 100, 80 and 20 percent.

At the macroscopic level, peak responses are reduced with decreasing depths of modulation for the 101.6 Hz modulation frequency, for both subjects (Figures 8 and 11). At the microscopic level, the patterns of response within modulation cycles change a bit with a reduction in modulation depth from 100 percent to 80 percent, and change substantially with a reduction from 80 percent to 20 percent (Figures 9 and 12). For subject SR2 the response to pulse five in each cycle is greater with 80 percent modulation than with 100 percent modulation (top two panels in Figure 9). The response to pulse six is somewhat lower with 80 percent modulation than with 100 percent modulation. Presumably, the higher amplitude of pulse five for the 80 percent modulation condition (0.924 versus 0.905 for the 100 percent modulation condition) produces a greater neural response. The subsequent response to pulse six may be reduced compared to the response for the 100 percent modulation condition, due to a larger proportion of neurons in a refractory state with the prior stimulation by pulse five.

For subject SR3 the response to pulse four is larger with 80 percent modulation than with 100 percent modulation (top two panels in Figure 12). The response to pulse five is somewhat diminished for the 80 percent modulation condition compared with the response for the 100 percent modulation condition. The mechanisms underlying these changes for SR3 may be the same as those suggested above for SR2.

In contrast to these relatively minor changes, large changes are observed in the patterns of response for both subjects between the 80 and 20 percent modulation conditions. For subject SR2 a clear response is elicited by the first pulse for the 20 percent modulation condition. Responses to subsequent pulses in each cycle of the modulation waveform show a more graded response compared with the responses for the 80 and 100 percent modulation conditions. In fact, the pattern of responses for the 20 percent modulation condition looks almost sinusoidal for the initial 100 ms of the record (Figure 9). Peak magnitudes of responses are much lower for the 20 percent modulation condition, presumably due to prior stimulation of relatively large numbers of neurons with relatively high pulse amplitudes.

The overall response for the 20 percent modulation condition is somewhat greater for subject SR3 (Figure 12). For her, the response to the very first pulse is quite large. An initial alternation in responses not observed for SR2 is seen in the record for SR3 over the first five pulses. As with the presentation of identical pulses at the carrier rate (see middle panel of Figure 6), the diminished

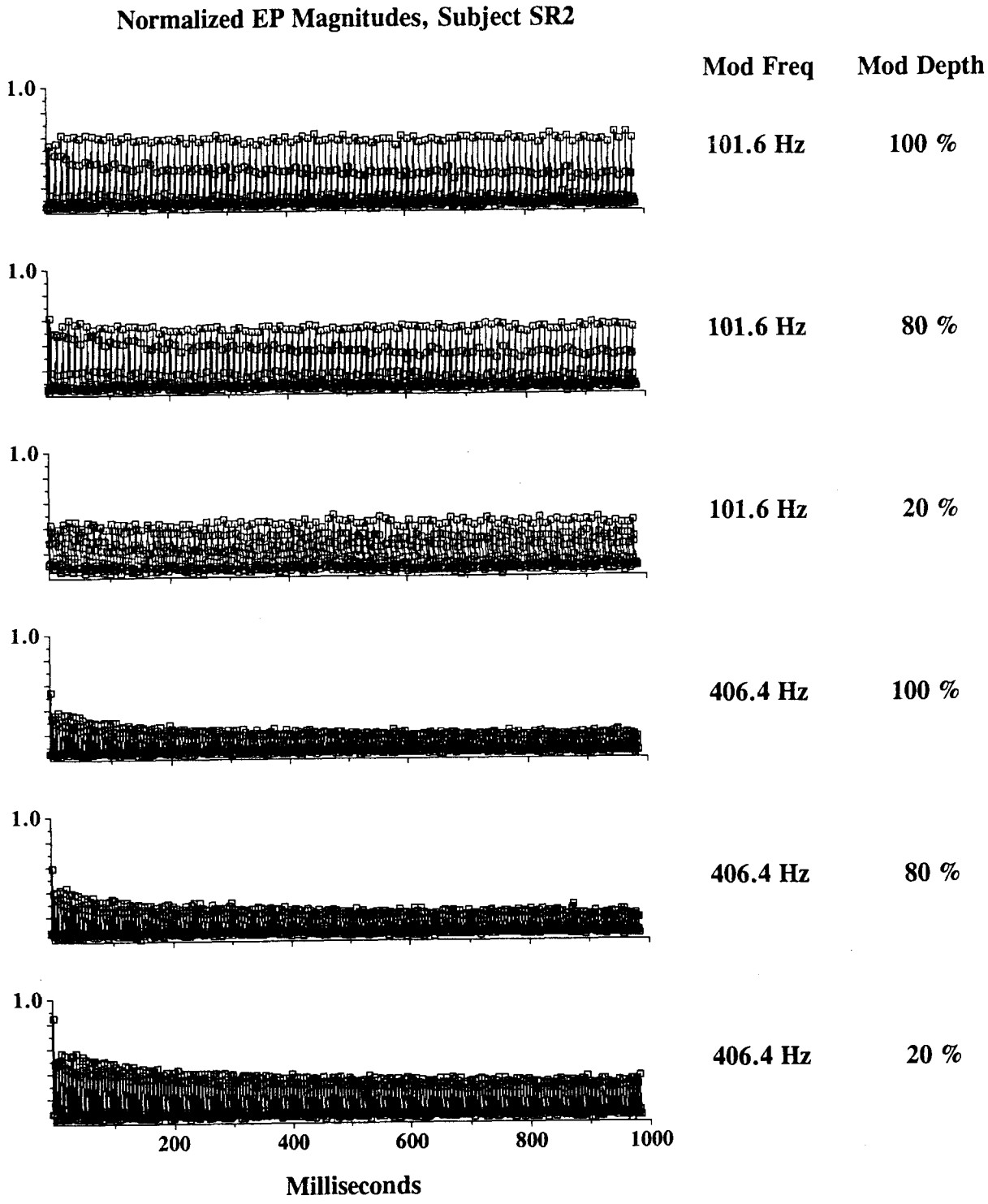

Figure 8. Normalized EP magnitudes for SAM pulse trains, Ineraid subject SR2. Carrier pulses were 32.8 μs/phase in duration and were presented at the rate of 1016/s. Recording conditions and other conditions of stimulation were the same as those described in the caption for Figure 2.

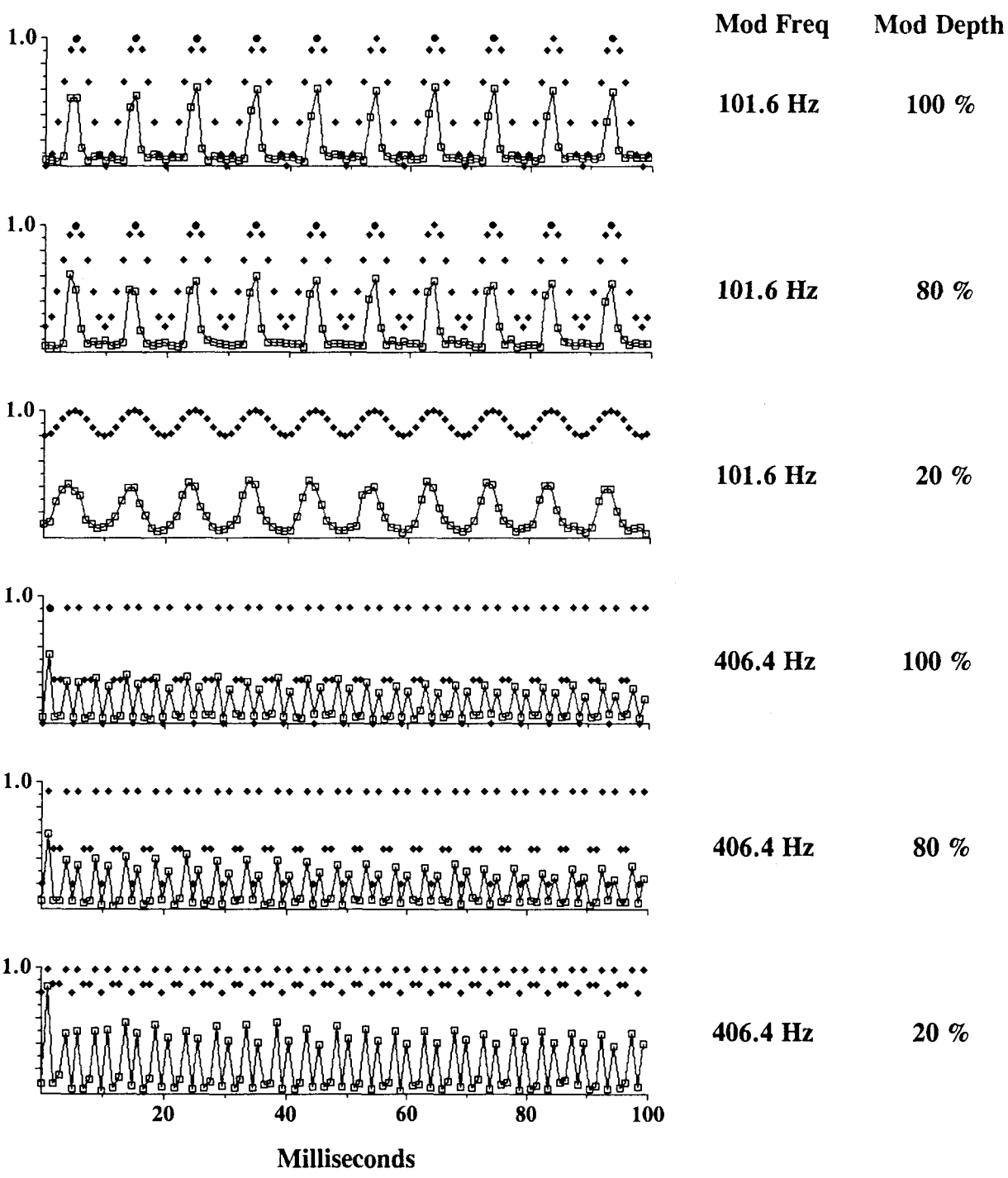

Figure 9. First 100 ms of the records shown in Figure 8. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

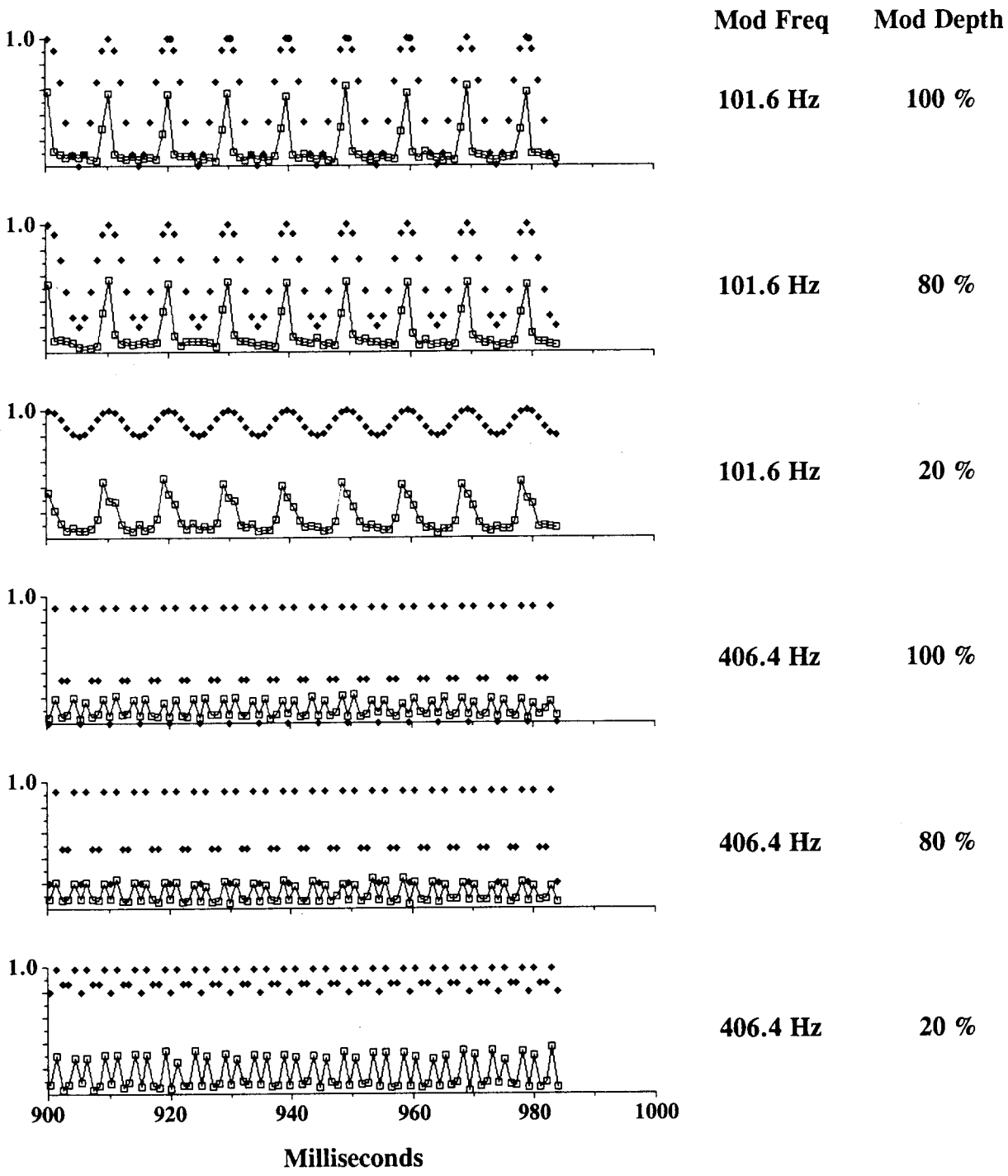

Figure 10. Final 100 ms of the records shown in Figure 8. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

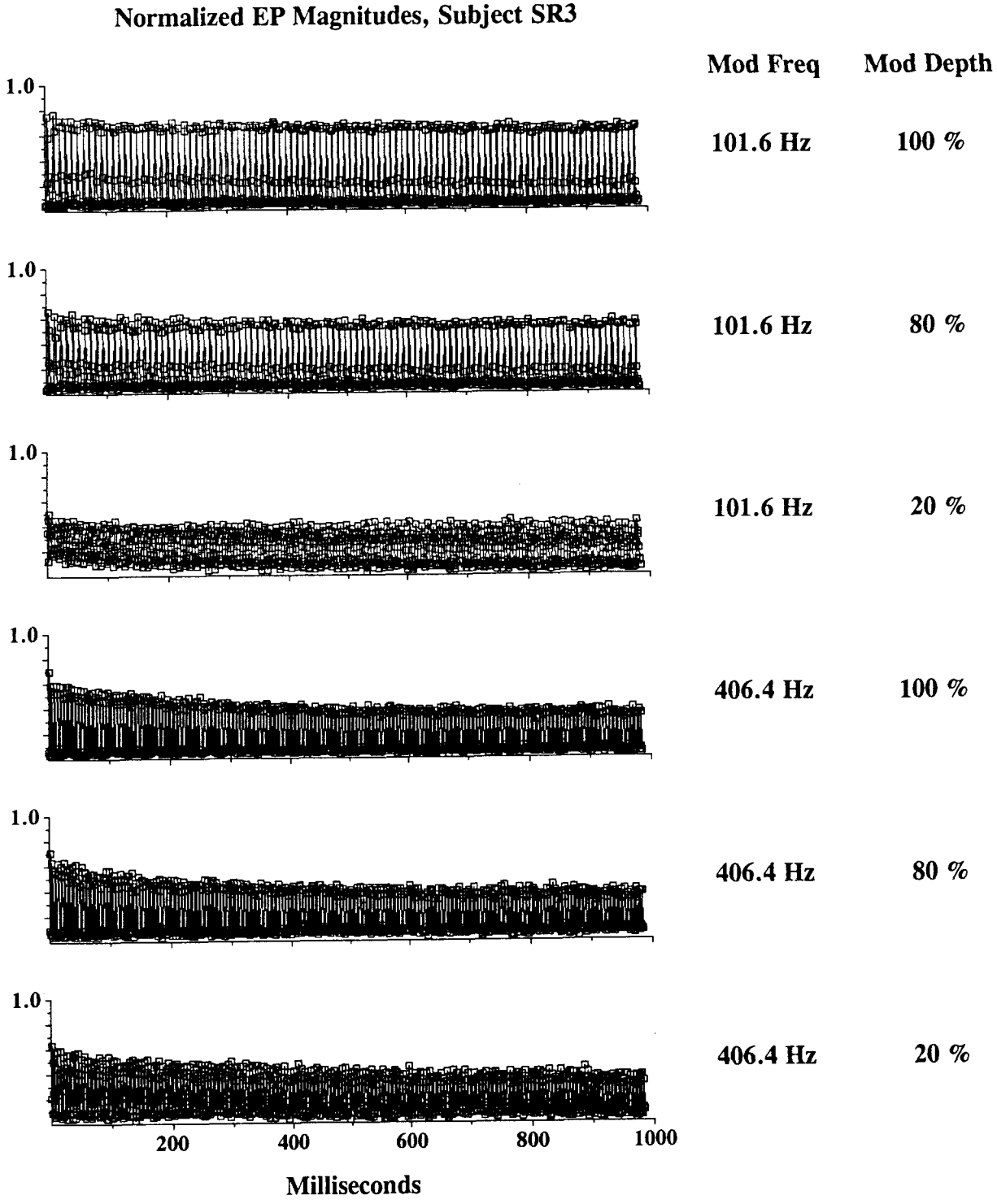

Figure 11. Normalized EP magnitudes for SAM pulse trains, Ineraid subject SR3. Carrier pulses were 32.8 μs/phase in duration and were presented at the rate of 1016/s. Recording conditions and other conditions of stimulation were the same as those described in the caption for Figure 5.

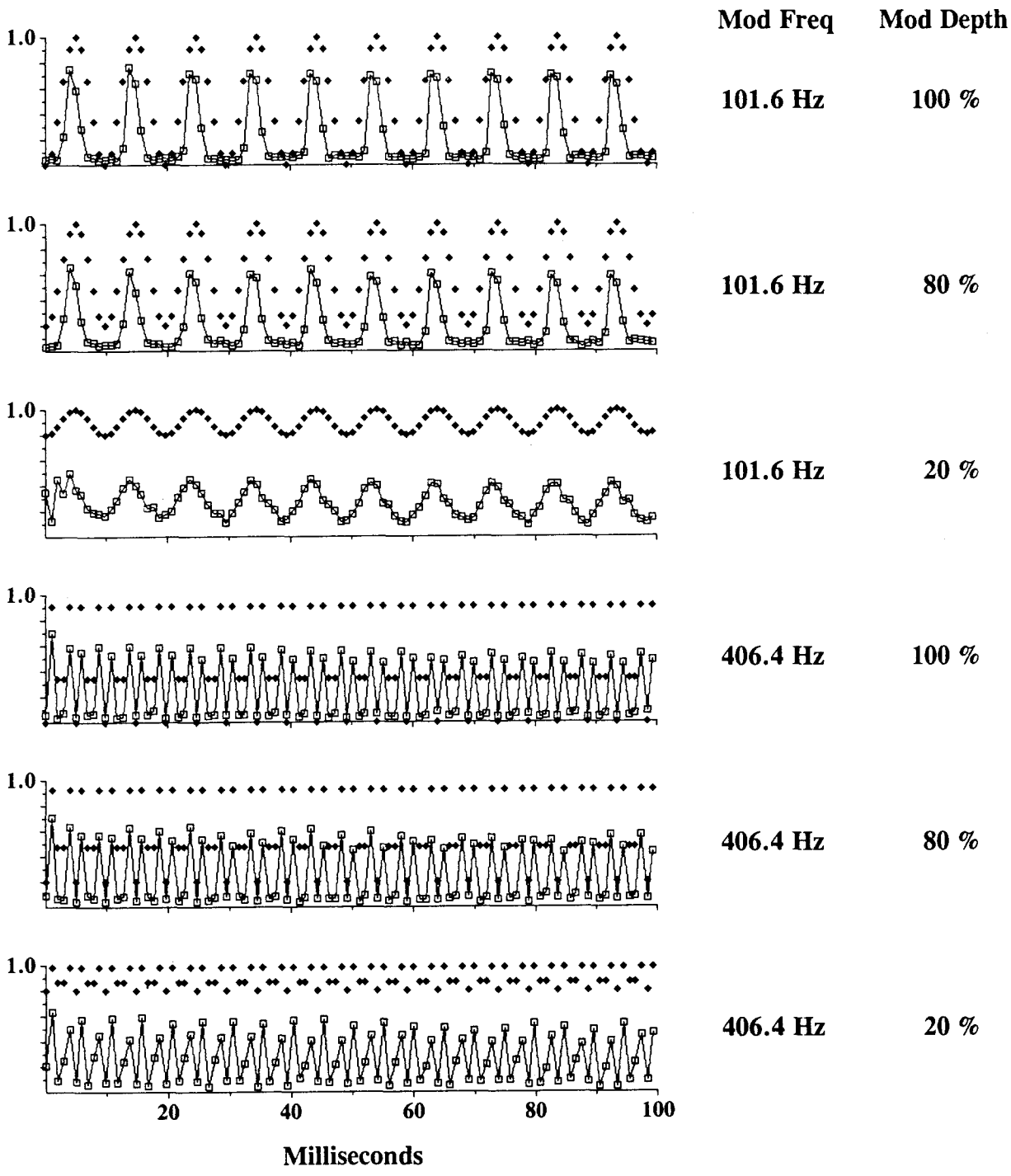

Figure 12. First 100 ms of the records shown in Figure 11. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

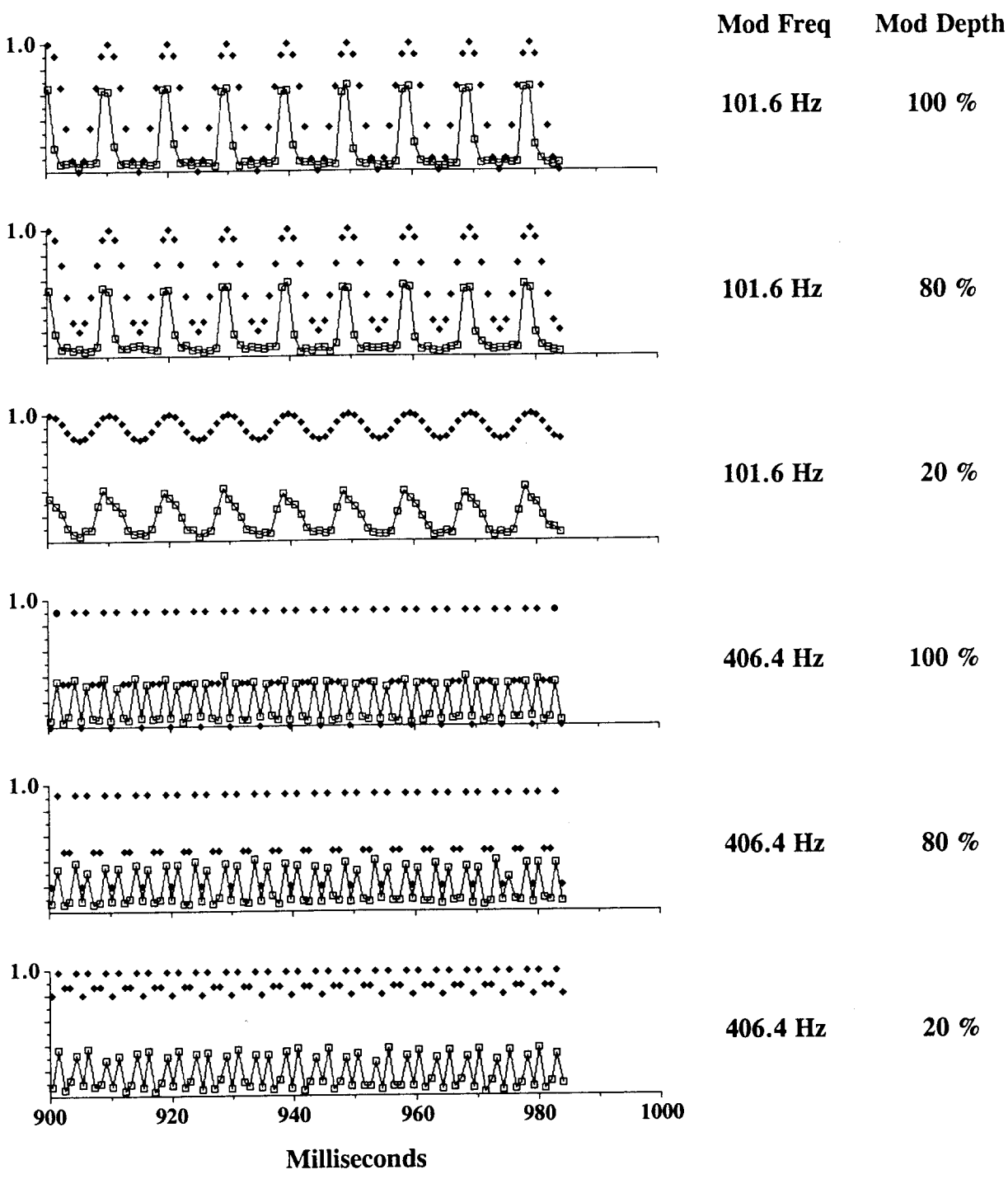

Figure 13. Final 100 ms of the records shown in Figure 11. Open squares show normalized EP magnitudes and filled diamonds show normalized pulse amplitudes.

response to pulse two may be an expression of refraction in the nerve. Responses to the subsequent pulses may reflect an alternating pattern of partial recovery and refraction, as described before for stimulation with identical pulses at 1016 pps.

Following these "start up" phenomena in the first cycle, the pattern of neural responses approximates a sinusoidal waveform, as with the responses for subject SR2. In SR3's case, however, even the smallest responses in the valleys of the modulation are clearly detectable, at least for the first 100 ms of the record.

As with the 100 percent modulation condition, responses for the 80 and 20 percent conditions change somewhat by the final 100 ms in the one-second records. Responses to pulse five in each cycle for SR2, and to pulse four for SR3, are diminished in the final 100 ms for the 80 percent modulation condition (compare Figures 9 and 10 for SR2 and Figures 12 and 13 for SR3). Similarly, responses to pulse four for SR2, and to pulse three for SR3, are diminished in the records for the 20 percent modulation condition. Also, the magnitudes of the EPs in the valleys of the modulation waveform approximate the noise floor of detectable responses by the end of the record for the 20 percent modulation condition for SR3. In all, the patterns of responses at the ends of these records for both subjects show a greater "peaking" of the response waveform, and somewhat less fidelity to the modulation waveform, than in the beginnings of the records.

In contrast to the macroscopic pattern observed for 101.6 Hz modulation, reductions in modulation depth for the 406.4 Hz modulation conditions produce increases in peak levels of response for subject SR2 (Figure 8). The increase is small for the reduction in depth from 100 percent to 80 percent, and the increase is relatively large for the reduction in depth from 80 percent to 20 percent.

A small increase in peak levels of response also is observed with a reduction in modulation depth from 100 percent to 80 percent for SR3 (Figure 11). In contrast to the finding for SR2, however, the further reduction in modulation depth, from 80 to 20 percent, produces a small decrement in peak levels of response.

For 406.4 Hz modulation, a reduction in modulation depth actually produces an increase in the peak amplitudes of stimulus pulses (see, e.g., bottom three panels in Figure 9). The normalized peak level for the 100 percent modulation depth condition is 0.905, whereas the peak amplitudes are 0.924 and 0.981 for the 80 and 20 percent conditions, respectively.

The higher amplitudes of pulses with increasing depths of modulation would be expected to produce higher levels of neural response, in the absence of other factors. However, as noted before, increasing amplitudes of pulses preceding the pulses with the greatest amplitudes also would be expected to elicit higher levels of neural response. Such higher levels of response to pulses preceding the peak-amplitude pulses would place a greater number of neurons in a refractory state at the time of the peak pulse, reducing the response to that pulse.

It seems likely that the macroscopic patterns of responses for the 406.4 Hz modulation conditions reflect a delicate balance between these two effects. For SR2 increases in the peak amplitude of

stimulus pulses with reductions in modulation depth appear to be most important. For SR3 refractory effects produced by pulses preceding the pulses with the peak amplitudes appear to have a strong influence for the 20 percent modulation condition, where a slight reduction in the peak levels of neural response is observed.

For pulses following the first cycle of modulation, detailed patterns of response for both subjects exhibit only minor changes with a reduction in modulation depth from 100 percent to 80 percent. The further reduction, from 80 percent to 20 percent, produces an increase in the response to pulse four in each modulation cycle and a relative decrease in the response to pulse five. As with 101.6 Hz modulation, the pattern of response at 20 percent modulation is a closer approximation to the modulation waveform than the patterns observed for 80 percent modulation and for 100 percent modulation. With 406.4 Hz modulation, however, the pattern at 20 percent modulation does not appear to be sinusoidal because the modulation waveform is only coarsely sampled by the carrier pulses.

Responses to the Pulsatile Outputs of Single-Channel Speech Processor

To examine the neural representation of more complex stimuli with implants, we also have recorded evoked potentials in response to the pulsatile outputs of a single-channel speech processor. The processor was a single-channel variation of CIS processors, which we call a *continuous sampling* (CS) processor, since interleaving is not relevant when there is only one channel. The CS processor uses the same front end as CIS processors, with a pre-emphasis filter (attenuation of 6 dB/octave below 1.2 kHz) and the same envelope detector and mapping function as in each CIS channel. The bank of bandpass filters is omitted in the CS processor, so the input to the envelope detector is the broad band speech signal, as modified somewhat by the pre-emphasis filter.

An example of the presented stimuli and recorded responses for one of the tokens in our consonant test, /asa/, is presented in Figure 14. As with the prior recordings, the stimuli were delivered to electrode 3 in the Ineraid implant (with reference to a remote electrode in the temporalis) and recordings were made differentially between the adjacent electrode 4 and an external electrode at the ipsilateral mastoid. Stimulus pulses were 32.8 μs/phase in duration, and were presented at the rate of 824/s. Normalized amplitudes of the pulses are shown in the top panel of Figure 14 and normalized magnitudes of the EPs following each pulse are shown in the bottom panel. The initial /a/ occurs during the first 140 ms of the records, the /s/ in the interval from about 190 to 330 ms, and the final /a/ in the interval from about 350 to 640 ms. These recordings were obtained in studies with subject SR2.

In broad terms, the neural response reflects the relatively deep modulations of pulse amplitudes during the /a/ segments and the relatively small differences among pulse amplitudes during the /s/ segment. Peak magnitudes of the response are greatest during the /a/ segments, where the pulse amplitudes reach peak levels.

The pattern of response to the temporal fine structure of stimulus pulses during the initial 100 ms of the records is shown in Figure 15. Here, normalized pulse amplitudes and normalized EP magnitudes are plotted in the same panel to facilitate comparisons.

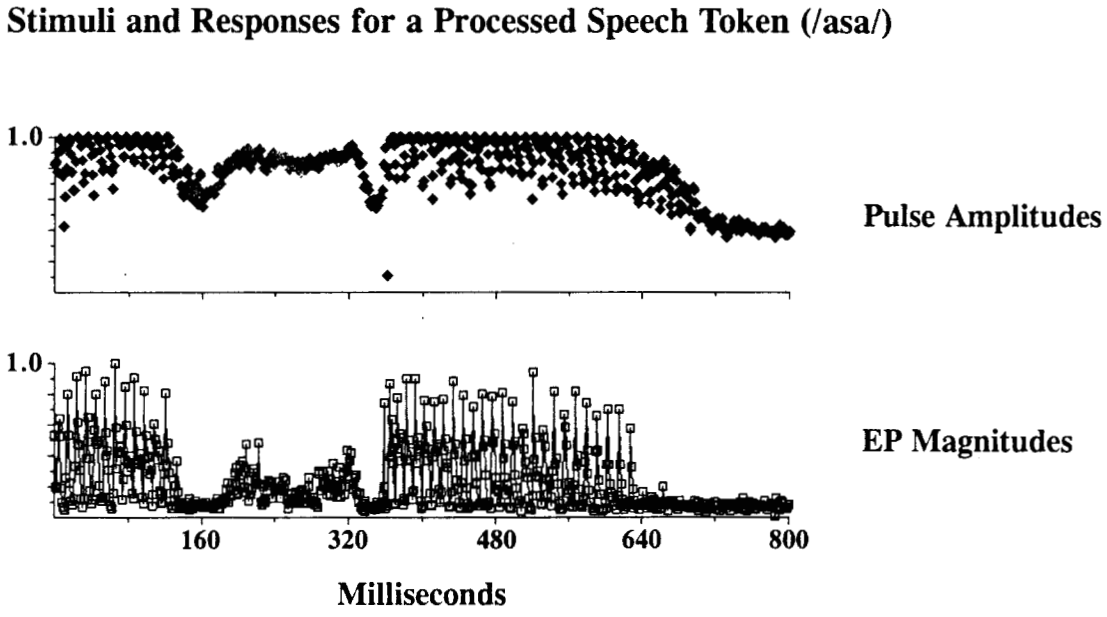

Figure 14. Normalized pulse amplitudes (top panel) and normalized EP magnitudes (bottom panel) for a processed speech token. A continuous sampling (CS) processor was used to process the speech token /asa/. Neural responses to the output of the processor were recorded for Ineraid subject SR2, as described in the text.

Although the pattern of responses reflect the fundamental frequency of the vowel, with peaks in the response at the first intense stimulus pulse in each (approximately 10 ms) period, other features in the stimulus are not represented. In periods two through eight, for instance, a series of three or more pulses with identical or nearly identical amplitudes is presented at the beginnings of the periods. The neural response to the first pulse in each of these periods is large, as noted before. However, the response to the second pulse is much smaller in all cases. Responses to subsequent pulses show an alternating pattern, much like the one observed before for identical pulses presented at the rate of 1016/s for this subject (middle panel of Figure 3). Thus, the pattern of response to these subsequent pulses in each period appear to reflect primarily properties of the auditory nerve, as opposed to the pattern of stimulation (and intended pattern of response).

The overall level of response during the /s/ segment appears to be depressed in relation to the pulse amplitudes. Figure 16 shows, however, that EP magnitudes for pulses of the same amplitudes are quite similar for the /a/ and /s/ segments. If any fatigue or accommodation occurs over the course of the /s/, it must be quite small.

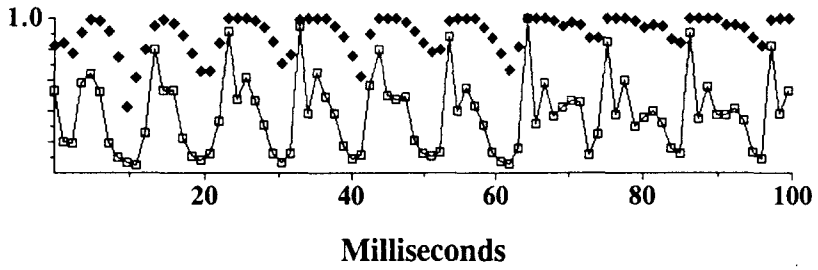

Figure 15. First 100 ms of the records shown in Figure 14. Open squares show normalized EP magnitudes and filled triangles show normalized pulse amplitudes.

Discussion

Responses to identical pulses presented at the rates of 401 and 1016/s show a slow decrement in response over time for both studied subjects. The magnitudes of EPs appear to approach a steady-state response 300 to 400 ms after the beginning of stimulation.

An alternating pattern of response to the initial pulses also was observed with these stimuli for both subjects. The pattern persisted across the first eight to ten pulses presented at 401 pps for subject SR2, and across the first three pulses for SR3. The pattern persisted for at least the first 100 ms for pulses presented at 1016 pps for both subjects. The difference between alternating high and low responses was greater for subject SR2 at 401 pps and somewhat greater for subject SR3 at 1016 pps. Differences in the amplitudes of alternating responses, and in the rates at which an alternating pattern is first observed, may reflect differences across patients in the number and physiological properties of surviving neurons, as suggested in QPR 7 for this project.

It is worth noting that the stimulus levels required to produce percepts of approximately equal loudnesses were substantially higher for subject SR3 (e.g., an MCL percept was produced with 290 μA pulses presented at 1016 pps for subject SR2, whereas 520 μA pulses were required to produce an MCL percept for SR3). However, the magnitudes of evoked potentials were similar for the two subjects (e.g., peak magnitude of 90.2 μV across the conditions of Figure 2 for SR2, versus 104.3 μV across the conditions of Figure 5 for SR3). The functional significance of such differences in required stimulus amplitudes among subjects has yet to be identified.

Responses to SAM pulse trains are maintained at a relatively high level throughout a one second stimulus. A small decrement in the response occurs over time for the 400 Hz modulation condition. The magnitude of the decrement appears to be less than that observed for identical pulses presented at

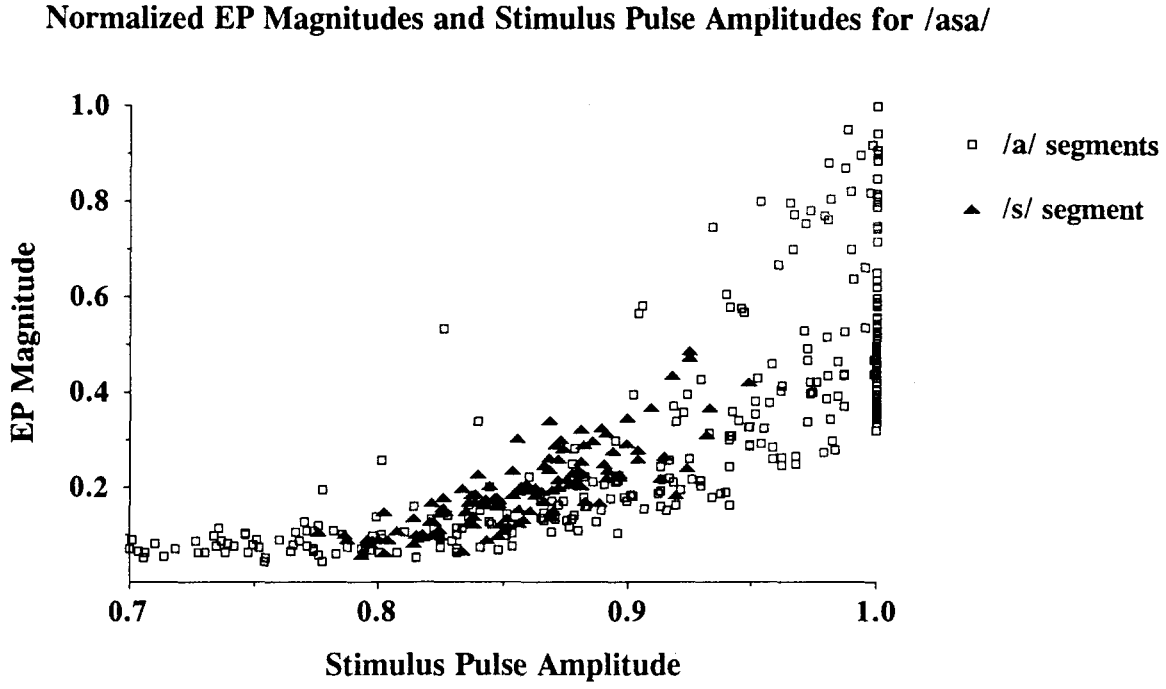

Figure 16. Scatter plot of normalized EP magnitudes versus normalized stimulus magnitudes for the speech token /asa/. Open squares show EP and stimulus magnitudes during the /a/ segments, and filled triangles show those magnitudes during the /s/ segment. The EP magnitudes are derived from recordings of neural responses in studies with Ineraid subject SR2 and correspond to the data also presented in Figures 14 and 15.

the modulation frequency.

Reduction in the depth of modulation can improve substantially the fidelity of neural following to the modulation waveform. The pattern of neural responses is almost sinusoidal for a 20 percent depth of sinusoidal modulation for both subjects, for the 100 Hz modulation condition.

This suggests the importance of mapping functions and the range over which stimuli are presented to implant patients. Mapping from threshold (or higher) values seems appropriate. Indeed, in our hands mapping from subthreshold values has produced decrements in speech reception performance and the judged naturalness or quality of speech percepts with CIS processors.

Patterns of response to processed speech stimuli appear much as would be predicted from the patterns of response to simpler stimuli. For presentation of sequential pulses with identical or nearly identical amplitudes, one could predict that, for pulses rates approximating 1000/s, a large EP would be elicited by the first pulse in the series, a much smaller EP by the second pulse, a partial recovery of the EP for the third pulse, and so on. Such patterns are observed during the vocalic segments of the example

speech stimulus.

Also, responses to SAM pulse trains with high modulation depths (80 or 100 percent) show a "peaking" of the neural response to a particular phase of the modulation waveform. Details other than the timing of that phase are represented poorly if at all in the response. In the example shown for the processed speech token, modulation depths approximate 40 percent or greater during the vocalic segments. As might be predicted from the results from studies with SAM pulse trains, the patterns of response to the processed speech stimulus show strong peaking in the responses, with peaks occurring at the fundamental frequency of the vocalic segments. Other details in the stimulus are not represented.

The fidelity of neural following to variations in pulse amplitudes might be improved through a change in the mapping function, e.g., a more compressive mapping function as suggested before by the patterns of responses to SAM pulse trains with a 20 percent depth of modulation. Also, successful application of any of the repair strategies outlined in QPR 9 for this project might be helpful. An observation for now is that temporal representations with implants are crude and highly limited, even for the best patients. Performance of these devices might be improved substantially with an amelioration or repair of such defects.

In broad terms, patterns of responses to pulse trains and SAM pulse trains are remarkably similar for the two subjects of this report. Additional subjects need to be studied to evaluate the generality of these initial findings. The additional subjects should include implant users at the low end of the clinical performance spectrum.

III. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. Presentation of project results in an invited lecture at the NIH Consensus Development Conference on Cochlear Implants in Adults and Children, to be held in Bethesda, MD, May 15-17 (Wilson).
2. Initial studies with the fourth of six patients in the Nucleus percutaneous series (NP4, June 19-30) and continued studies with the second patient (NP2, July 10-21). Studies with NP4 will include evaluations of CIS and SPEAK processing strategies. Studies with NP2 will include repeated measures with the SPEAK strategy, detailed evaluation of CIS processors using more than six channels, and measures of intracochlear evoked potentials.
3. Continued analysis of speech reception and evoked potential data from prior studies, and continued preparation of manuscripts for publication.

IV. Acknowledgments

We thank subjects SR2 and SR3 for their enthusiastic participation in our studies.

Appendix 1

Summary of Reporting Activity for the Period of

February 1 through April 30, 1995

NIH Project N01-DC-2-2401

Reporting activity for the last quarter included the following presentations:

Wilson BS, Lawson DT, Zerbi M, Finley CC: New developments in speech processors. Invited lecture, Workshop in Auditory Prosthetics, *Midwinter Meeting of the Association for Research in Otolaryngology*, St. Petersburg, FL, Feb. 5-9, 1995.

Finley CC, Wilson BS: Responses of the auditory nerve to repetitive electrical stimuli as demonstrated with recordings of intracochlear evoked potentials. Poster presentation, *Midwinter Meeting of the Association for Research in Otolaryngology*, St. Petersburg, FL, Feb. 5-9, 1995.

Lawson DT: Design and performance of speech processors for cochlear prostheses. Invited lecture, Otolaryngology Grand Rounds, Duke University Medical Center, Feb. 15, 1995.

Wilson BS, Finley CC: Temporal representations with cochlear implants. *IIIrd International Congress on Cochlear Implant*, Paris, France, April 27-29, 1995.

Wilson BS (Chair), Cazals Y, Dillier N, Mac Leod P, McDermott H, Pelizzone M (panelists): Round Table on Sound Signal Processing. *IIIrd International Congress on Cochlear Implant*, Paris, France, April 27-29, 1995.

Wilson BS: Future directions in speech processing. Invited lecture, CIS Workshop (sponsored by Med El GmbH), Paris, France, April 26, 1995.