Eleventh Quarterly Progress Report

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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 it 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:

- A visit by Dr. Artur Lorens, of the International Center of Hearing and Speech in Kajetany (near Warsaw), Poland, October 18-20.
- Presentation by Blake Wilson, to provide an "Update on EAS studies at the Research Triangle Institute," at the Hearing Preservation Workshop III, held in Dallas, TX, October 15-17.
- Session on Neural Enhancement chaired by Blake Wilson at the Hearing Preservation Workshop III, Dallas, TX, October 15-16.
- Continued development of hardware and software tools for full laboratory control of the new Med-El PULSAR$_{CI}^{100}$ implant system.
- A visit by consultant Mariangeli Zerbi, to assist in this effort, November 11-14.
- Studies with subject NP-6, implanted with an experimental version of the Nucleus device that provides percutaneous access to a Contour electrode array, November 15-16. The studies included evaluation of various CIS processors using tests of consonant identification.
- Presentation by Blake Wilson on "The auditory prosthesis as a paradigm for successful neural interfaces," at the Neural Interfaces Workshop, National Institutes of Health, Bethesda, MD, November 15-17.
- Continuing studies with subject NP-8, another of the four recipients of the experimental Nucleus device, November 22-23. The studies with this subject included evaluation of various CIS processor designs, all using an extended analysis frequency range of 80-7000 Hz, and some using current steering between simultaneously stimulated electrodes to produce virtual channels or pitches. Sites of stimulation (and their corresponding pitches) were selected dynamically in the latter processors using instantaneous frequency signals derived from the phase output of Hilbert Transforms for each processing channel. The measures for all of the processors included recognition of CUNY sentences presented in competition with speech-spectrum noise.
- Presentation by Blake Wilson on "Speech coding for bilateral cochlear implants," at the 5th Wullstein Symposium on Bilateral Cochlear Implants and Binaural Signal Processing, Würzburg, Germany, December 2-6.

- Studies with subject NP-9, another recipient of the experimental Nucleus device, December 6-10. The studies with this subject included ranking of electrodes according pitch; evaluation of a variety of CIS processor configurations using tests of consonant identification; and recording of intracochlear evoked potentials to "split-phase" stimuli with a 3 ms inter-phase gap, to measure neural population responses to single polarities of stimulation (while still maintaining charge balancing for safety of stimulation).
- Further enhancement of capabilities for streaming-mode stimulation, as originally described in Quarterly Progress Report 5 for this project.

In addition to the above-mentioned activities, work continued on the analysis of previously collected data, the design of signal processing strategies for representing fine-frequency information, and acoustic simulations of such processing strategies for tests with normal hearing persons.

In this report we provide a description of the hardware and software tools that have recently been developed for full laboratory control of the new Med-El PULSARCI^{100} implant. These tools together provide an interface to the implant and allow complete access to its advanced features.

We were assisted in the development of the interface system by Otto Peter, Clemens Zierhofer, Erwin Hochmair, and others at the University of Innsbruck, in Innsbruck, Austria, and at the Med-El GmbH, also in Innsbruck. We are most grateful for their invaluable help.

In Appendix 2 we also describe the new extensions to the system used for streaming-mode stimulation. Results from other studies and activities indicated above will be presented in future reports.

II. Laboratory interface for the new Med-El PULSAR$_{CI}^{100}$ implant

The PULSAR$_{CI}^{100}$ (PULSAR) implant received market approval for the European Union in the spring of 2004. This implant now is used routinely throughout the EU and may soon be applied in the United States as well, pending final FDA approval. Many aspects of the implant are described in Zierhofer, 2003. The design includes a novel method for envelope detection, used in this case for demodulation of a radio-frequency (RF) carrier, and a novel method for presenting stimulus pulses in strict synchrony across multiple electrodes. The method for envelope detection provides the same function as conventional approaches, but with much lower power consumption.

In the remainder of this section we provide (1) a brief overview of the specifications and capabilities of the new device; (2) a description of the interface system we have developed for full laboratory control of a unilateral PULSAR implant, or of bilateral PULSAR implants; and (3) a description of updates to our monitor (controlling) program, for implementation of various psychophysical tests in conjunction with the new interface system. The work described puts us in a position to exploit fully the capabilities of the new device, including synchronous control of bilateral implants and including current steering between (or among) simultaneously-stimulated electrodes within an implant.

A. Specifications and capabilities of the new implant

The basic features of the PULSAR can be summarized as follows:

- The same electrode array as in the COMBI 40+ implant, with 12 intracochlear sites of stimulation.
- Better current sources compared with the COMBI 40 and COMBI 40+ implants, with highly linear operation up to the maximum current of 1.2 mA.
- A total of 24 current sources, for stimulation with both polarities at up to 12 sites.
- Blocking capacitors at the outputs of the current sources, to assure charge balancing at the electrodes under any condition.
- Capability to present pulses simultaneously at up to 12 electrodes and with no offsets in time among pulses.
- A mode for rapid sequential stimulation across all or any subset of electrodes at an aggregate rate of up to 50760 pulses/s across all addressed electrodes. (For a 12-channel processor, rates as high as 4230 pulses/s/electrode can be supported.) This aggregate rate is almost three times that of the COMBI 40+. In addition, the better current sources of the PULSAR may allow the effective use of shorter pulses and higher rates as compared with the COMBI 40+.
- A choice among stimulus waveforms, including biphasic or triphasic waveforms, with either polarity for the first phase, anodic or cathodic.
- A specified inter-phase gap of 2.1, 10.0, 20.0, or 30.0 µs for each of the stimulus waveforms.
- An optional dynamic extension of a pulse phase duration in 25% increments up to a doubling of the original duration.

- Back-telemetry of implant status and electrode impedances.
- Back-telemetry of intracochlear evoked potentials. Measurement of the potentials is accomplished with an instrumentation amplifier (40 dB gain) followed by a stage of adaptive sigma-delta modulation for sampling the amplifier output with high resolution and low noise (see Zierhofer, 2000). This system for measurement and back telemetry of intracochlear evoked potentials is called the Auditory Nerve Response Telemetry (ART) system.
- A back-compatibility mode to emulate the operation of the prior COMBI 40 or 40+ implants. (Neither of these prior implants include an ART capability.)

The currents generated by the PULSAR are directed to the implanted electrodes in a monopolar configuration, i.e., currents are applied across an intracochlear electrode and a remote reference electrode implanted in the temporalis muscle, as in the COMBI 40 and 40+ implants. Recordings of intracochlear evoked potentials are made with an intracochlear electrode other than the stimulating electrode, with reference to a remote electrode on the case of the implanted receiver/stimulator.

Pulse waveforms and timing

Illustrations of stimulus waveforms and timing supported by the PULSAR device are presented in Figures 1 and 2, respectively. Three waveforms are supported, including conventional biphasic pulses and two variations of triphasic pulses. The first variation of triphasic pulses uses the same amplitude for each of the three phases and sets the duration of phase 1 and of phase 3 to half that of phase 2 (middle panel of Figure 1). The second variation uses the same duration for each of the three phases and allows specification of the amplitudes for the first two phases, so long as the amplitude of phase 2 is greater than the amplitude of phase 1 (right panel). The amplitude of phase 3 is calculated as the difference in the amplitudes for the first two phases, A_2 - A_1. The net charge is zero for each of the three waveforms.

Triphasic pulses may offer advantages over biphasic pulses, as described for example in Eddington et al., 2004. However, use of triphasic pulses is still experimental and further studies are needed to evaluate their efficacy for cochlear implants. The PULSAR device provides a platform for such studies, including independent adjustment of the charges in phases 1 and 3 with the third stimulus waveform shown in Figure 1. This pulse type is called “triphasic precision.”

As noted above, stimuli may be presented sequentially across electrodes, or presented simultaneously to two or more electrodes. Groups of simultaneously-presented pulses also may be sequenced from one set of electrodes to the next. Some of these possibilities are indicated in Figure 2.

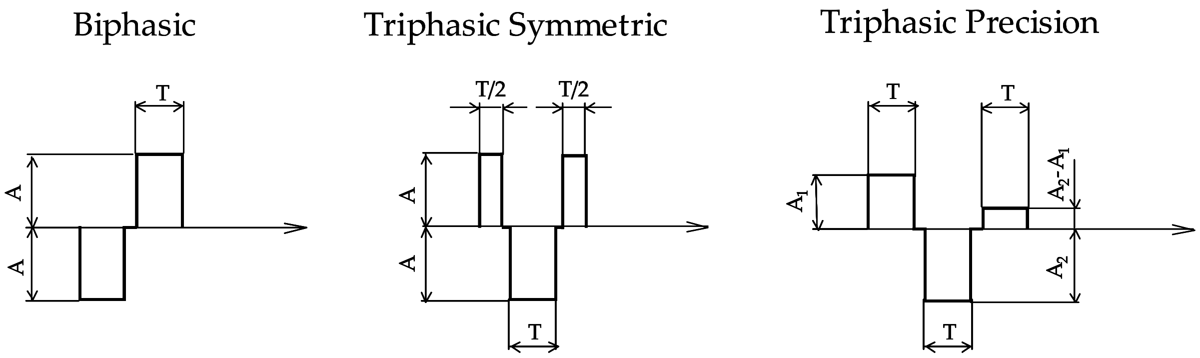


Fig. 1. Stimulus waveforms supported by the PULSAR device. The left panel shows a biphasic, cathodic-phase-first pulse with amplitude A and duration T. The two phases have identical durations and identical amplitudes, and only the polarity differs between them. The panel in the center shows a triphasic pulse with a +/–/+ phase polarity at the same nominal amplitude A and phase duration T as the biphasic pulse to the left. A zero net charge is achieved by setting the durations of the first and third phases equal to each other and to half the duration of the second phase. An alternative triphasic waveform that is supported by the device is shown in the right panel. In this case the same duration is used for each of the three phases. The amplitudes A_1 and A_2 are specified by the controlling software, and the hardware in the implanted receiver/stimulator calculates the amplitude A_3 as the difference between A_1 and A_2, $A_2 - A_1$ (A_2 must always be greater than A_1; this is assured through both software and hardware checks.) The controlling software can specify either a cathodic or anodic leading phase for each of the three stimulus waveforms.

Instructions are sent to the implanted receiver/stimulator of the PULSAR device using an RF link between induction coils, one outside the skin surface (on the scalp) and driven by external electronics and the other beneath the skin surface and connected to the receiver/stimulator. A series of logical ones and zeros is encoded in the RF signal using amplitude-shift-keying (ASK) modulation of a continuous carrier (following the modulation, the carrier is either present or absent for specified periods according to the modulation). This information is decoded in the receiver/stimulator using the novel envelope detector mentioned above. Energy in the RF signal also supplies power for the implanted receiver/stimulator.

Specification of stimuli

Pulse data are transmitted as a combination of static and dynamic information. Static information is valid for every stimulation pulse that follows its transmission and includes

- An identification (ID) code, unique to each implant and required to activate it
- Reference current range
- Phase duration
- Inter-phase gap

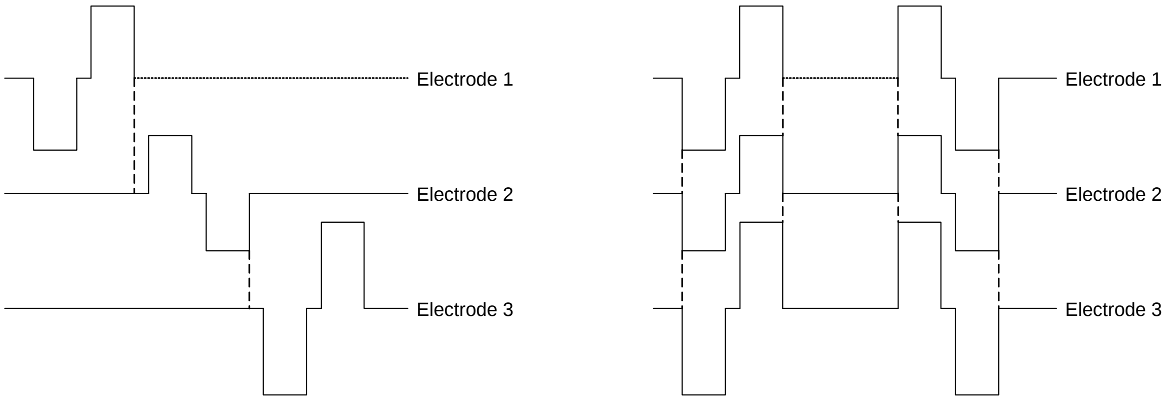


Fig. 2. Sequential and simultaneous stimulation with the PULSAR implant. In the left panel, sequential biphasic pulses (cathodic phase first on electrodes 1 and 3 and anodic first on electrode 2) are shown. The right panel shows sign-correlated biphasic pulses presented simultaneously at the same three electrodes. Note that the PULSAR device requires simultaneous pulses to have the same polarity, phase duration(s), and inter-phase gap.

Dynamic data can change from one pulse to the next and include

- Whether the simultaneous or sequential mode is to be used
- Pulse waveform
- Polarity of the first phase
- Electrode address(es)
- Pulse amplitude(s)
- Possible extension of phase duration by 125, 150, 175, or 200%

The static information may be updated at any time, e.g., to change pulse duration. The static information applies to all pulses since the most-recent update. The dynamic data can specify electrode addresses and pulse amplitudes for up to 12 sites of stimulation per data word, for the present electrode array with its 12 sites. Two amplitudes are specified for each pulse when the "triphasic precision" waveform is selected, as described above. (Note that generation of the sequential stimuli in the left panel of Figure 2 would require three separate dynamic data words, as the polarity of the leading phase changes from one electrode to the next.)

Maximum rates

The maximum rate of data word presentations is set by the total number of bits in the word. (The transmission rate of the RF link is 600k bits/s.) This will vary according to the pulse waveform selected, how many electrodes (and corresponding amplitudes) are included in each word, and whether an instruction is given to extend the phase duration.

In addition, certain "doublet" sequences can speed up the transmission of a given amount of information. These maximum rates establish in turn the maximum rates of pulse presentations at the electrode(s).

Maximum rates at each addressed electrode, in kilopulses/s, are shown in Table 1 for each of the three pulse waveforms. The rates for the triphasic symmetric pulses are similar to those for the biphasic pulses. The rates for the triphasic precision pulses are substantially lower than those for the other pulse types, due to the need to specify an additional amplitude value for the triphasic precision pulses. The maximum rates presented in Table 1 can be achieved if the phase duration is not extended. Rates are somewhat lower when this additional control is invoked. Aggregate rates for the sequential mode can be computed by multiplying the number of addressed electrodes by the corresponding rate indicated in the table.

In all, rates supported by the PULSAR implant are quite high. For example, rates can be as high as 4230 pulses/s/electrode with sequential or simultaneous stimulation of 12 electrodes using biphasic pulses. The aggregate rate across electrodes for sequential stimulation in this case is 50760 pulses/s.

Summary

The PULSAR implant provides a high degree of control over stimulus patterns, including stimulus waveforms, sequencing, and rates. Such flexibility offers possibilities for implementation of novel speech processor designs.

B. Interface for laboratory control of Med-El PULSARCI^{100} implants

Hardware and basic function

A block diagram of the PULSAR interface is shown in Figure 3. The interface is designed to support bilateral stimulation of two implants and provides precise synchronization of stimulation between the two sides. It also includes the hardware required for performing the various back-telemetry measures supported by the implant. However, the latter feature is not currently implemented in the interface software.

The hardware for the interface was developed in close collaboration with colleagues at the University of Innsbruck and Med-El GmbH, who designed and manufactured the interface’s printed circuit board and wrote the XILINX Spartan XL program for us. We are most grateful for their help and essential role.

The core of the interface consists of a XILINX XCS30XL Spartan-XL Field Programmable Gate Array (FPGA) and a 100-MHz Motorola DSP56309. Address, data and control buses connect the two devices with each other and to a Flash Programmable Erasable Read Only Memory (Flash PEROM, 512k x 8 bits) and a Static Random Access

Table 1. Maximum rates of stimulation for the three types of pulses supported by the PULSAR implant. Rates are given in kilopulses/s/electrode.

Number of addressed electrodes	**Pulse waveform**		
	Biphasic	**Triphasic symmetric**	**Triphasic precision**
1	28.57	26.08	17.65
2	18.75	17.65	11.54
3	13.95	13.33	8.57
4	11.11	10.71	6.82
5	9.23	8.96	5.66
6	7.89	7.69	4.84
7	6.90	6.74	4.23
8	6.12	6.00	3.75
9	5.50	5.41	3.37
10	5.00	4.92	3.06
11	4.58	4.51	2.80
12	4.23	4.17	2.59

Memory (SRAM, 512k x 24 bits). Additional control lines between the XILINX and DSP and the outside world include interrupt request, reset, and trigger input/output lines.

Communication between the interface and the ADS56301-based speech laboratory processor occurs over an Enhanced Synchronous Serial Interface (ESSI) connection between the interface's DSP56309 and the laboratory system's DSP56301. The interface is software-configured in the two DSP devices to transfer 24-bit data words (pulse data and pulse request words) in a full-duplex mode, at about 6 Mbits/s to support stimulation at the highest possible pulse rates on both sides. In addition to the ESSI port, the interface's DSP56309 can be accessed for debugging purposes through the Motorola On-Chip Emulator (OnCE) interface and a standard COM port connection to the DSP's Serial Communication Interface (SCI).

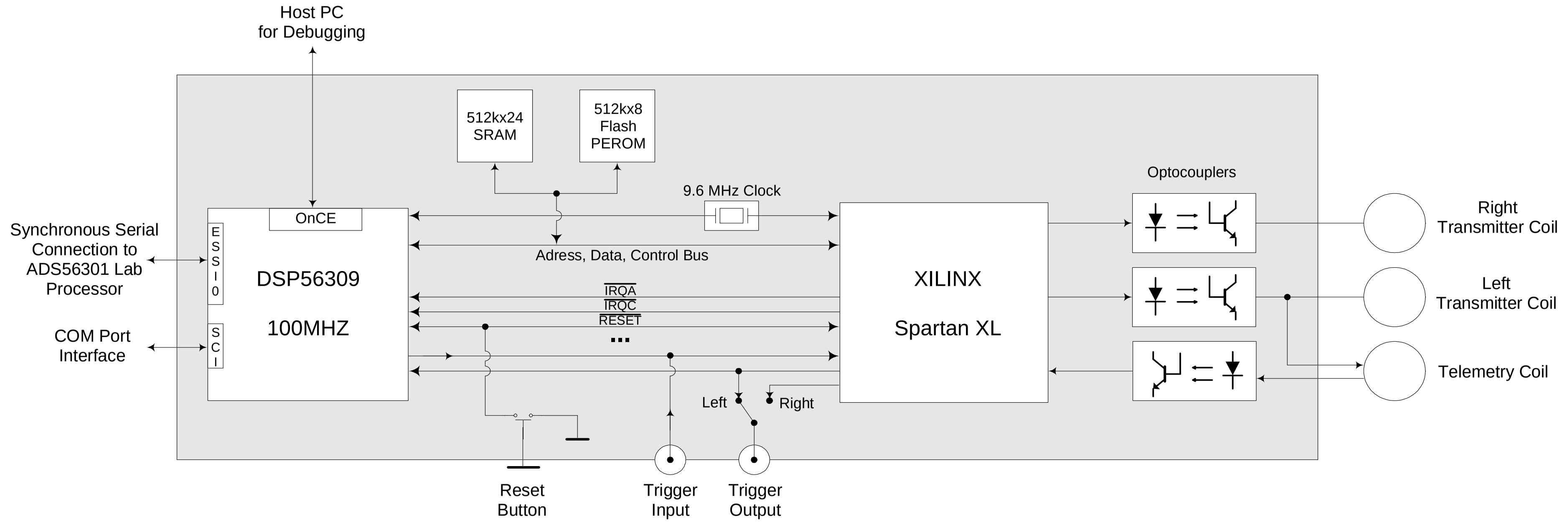


Fig. 3. Block diagram of the bilateral interface. Note that only the principal signals and hardware components are shown.

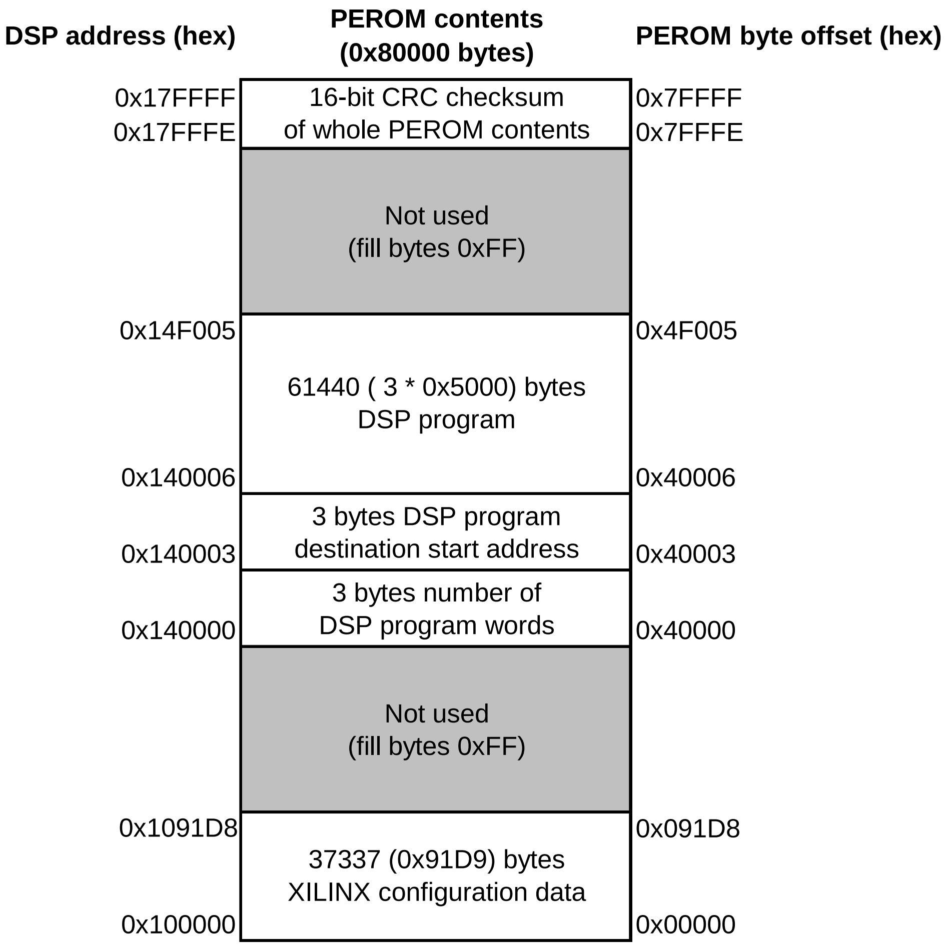


Fig. 4. Allocation of DSP and XILINX configuration data in the interface flash PEROM.

The interface is equipped with two 3-pin connectors for the left and right-side implant coils and one 4-pin connector for a telemetry coil, which shares the transmitter output signal with the left-side implant coil connector and adds an implant read-back signal pin. The driver stages for all implant transmitter connectors and the read-back signal receiver stage are galvanically isolated from the other, 5 VDC mains-powered interface components. Three high-speed Agilent HCNW2211 optocouplers provide isolation for the coil signal paths of up to 5000 Vrms for 1 minute per UL1577, and a PWR1300A DC/DC converter from CD-Technologies guarantees a 4000V isolation barrier per UL544 for the output stage power supply.

The flash PEROM holds the configuration data for both the DSP56309 and XILINX Spartan-XL devices, as shown in Figure 4. The on-board SRAM memory in the DSP is not needed nor utilized in the present application.

At startup or after an external reset, the DSP56309 boots from the byte-wide PEROM, retrieving and then executing its program, beginning at DSP address 0x140000 (physical

PEROM address 0x40000). Once initialized, the DSP releases the XILINX device from its reset state by initiating an express mode configuration cycle. During express configuration, the Spartan-XL device is initialized with configuration data that start at address 0x100000 (physical PEROM address 0x00000).

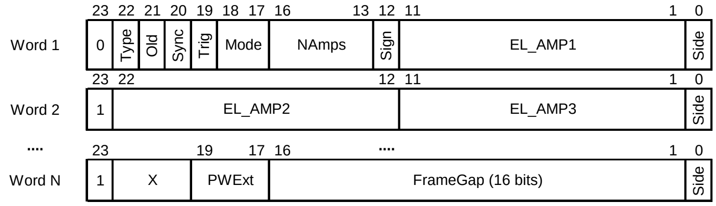
With both the XILINX and DSP initialized and running, the interface is ready to accept pulse data for either the left- or right-side PULSAR implant from the ADS laboratory processor. The principal task of the Spartan-XL device is to generate the left- and right-side transmitter signals, which are "on or off" RF carriers according to the bit patterns of the data words for each side (see below). The modulated RF carriers are transmitted to the implants via transcutaneous inductive links. The data that define the transmitter signals to be generated are written continuously from the DSP into two (one for each side) 63-stage deep First-In, First-Out (FIFO) buffers in the XILINX. The FIFOs are first completely filled with data by the DSP and then replenished in response to an interrupt signal (IRQA and IRQC for left or right-side FIFO, respectively), asserted by the XILINX whenever a FIFO contains less than 16 data words (a state referred to as "partially empty" in the discussion that follows). Immediately after initialization, and whenever a FIFO runs empty or is idling while waiting for both left and right FIFOs to be synchronized or for an external trigger to occur, the XILINX automatically generates a null-data sequence for the transmitter signal linked to the empty or idling FIFO.

The DSP56309 in the interface receives the data for the pulse sequences to be generated over the ESSI connection from the ADS laboratory processor. Whenever pulse data are received for a given side, the interface DSP requests new pulse data for that side by transmitting a side-specific request word back to the ADS processor. The pulse data received from the DSP56309 are defined in the compact format shown in Figure 5 and must be configured in the DSP into the transmitter signal "on/off" format recognized by the XILINX FIFOs, before being written to the XILINX. In addition to writing the transmitter signal data to the Spartan-XL, the DSP can also instruct the XILINX to synchronize the transmitter signal generation from the FIFO data between the two sides, and to generate an external trigger output signal or wait for a trigger input before initiating the generation of the transmitter signal from FIFO data.

The XILINX controls the timing of the transmitter signal generation and thus implicitly determines the rate at which FIFO data must be replenished from the interface DSP and, at the end of the data-supply chain, requested from the ADS laboratory processor by the interface DSP.

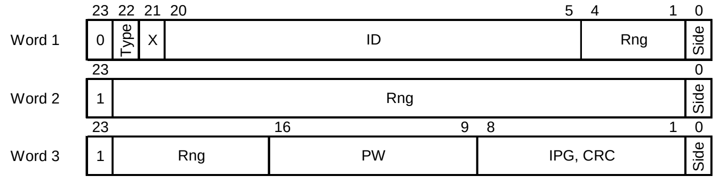
Figure 5 shows how the pulse data and request words transferred over the ESSI connection between ADS laboratory processor and interface DSP are specified. In order to start a stimulation sequence on a PULSAR implant receiver, first a static data block has to be sent by the laboratory processor. Acknowledged by the interface DSP with a request for new data on the same side where the static information has just been received, the ADS continues by transmitting a dynamic data block. Each subsequent dynamic

Dynamic pulse data format



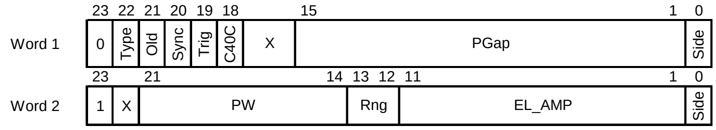
Bit 23 = 0	1st word in pulse data block (Bit 23 = 1 here reserved for cmd bit in Psycho pulse data tables)
1	All words other than 1st one in dynamic/static/old pulse data block
Type = 0	Dynamic data
Old = 0	Pulsar pulse data
Sync:Trig = 00	Send out pulse right away, without sync or trigger
01	Activate trigger output with this pulse
10	Synchronize this pulse with other side
11	Wait for external trigger input to send out pulse
Mode = 00	Biphasic
01	Triphasic symmetric
10	Triphasic precision (currently not supported)
NAmps	Number of EL_AMP values in this block (number of simultaneous/sequential pulses)
Sign = 0	Cathodic first
1	Anodic first
EL_AMPx	Electrode and pulse amplitude
PWExt	Number of dynamic phase-width extensions: 0 = 0%, 1 = 25%, 2 = 50%, 3 = 75%, 4 = 100% of original phase width
FrameGap	Gap count between pulse data frames transmitted to implant
Side = 0	Left side data
1	Right side data

Static pulse data format



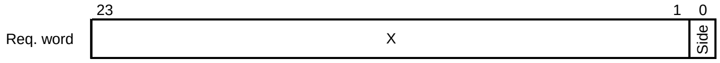
Bit 23 = 0	1st word in pulse data block (Bit 23 = 1 here reserved for cmd bit in Psycho pulse data tables)
1	All words other than 1st one in dynamic/static/old pulse data block
Type = 1	Static data
ID	Implant ID
Rng	Current ranges
PW	Phase width
IPG, CRC	Inter-phase gap and checksum
Side = 0	Left side data
1	Right side data

Pulse data format for old COMBI 40/40+ implants



Bit 23 = 0	1st word in pulse data block (Bit 23 = 1 here reserved for cmd bit in Psycho pulse data tables)
1	All words other than 1st one in dynamic/static/old pulse data block
Type = 0	Dynamic data
Old = 1	COMBI 40/40+ pulse data
Sync:Trig = 00	Send out pulse right away, without sync or trigger
01	Activate trigger output with this pulse
10	Synchronize this pulse with other side
11	Wait for external trigger input to send out pulse
C40C = 0	COMBI 40+ implant
1	COMBI 40 implant
PGap	Pulse gap count
PW	Phase width
Rng	Current range
EL_AMP	Pulse amplitude and electrode
Side = 0	Left side data
1	Right side data

Interface pulse data request word



Side = 0	Left side new pulse data request
1	Right side new pulse data request

Fig. 5. ESSI pulse data specification. The symbol X indicates "don’t care" bits.

information transfer (or new static data block) is again triggered by a request word from the interface DSP.

The specification in Figure 5 also includes a pulse data definition for the prior generations of Med-El implants, the COMBI 40 and 40+ stimulators. Support for those implant types is already implemented in the XILINX Spartan-XL, but not fully yet in the interface DSP firmware and higher-level control programs. Those remaining tasks could be completed quickly and without much additional investment, should patients with a PULSAR implant on one side, and a COMBI 40 or 40+ implant on the other side, become available for testing.

Interface DSP program

The Motorola DSP56309 device is the master unit controlling the operation of the interface. After booting from the external PEROM memory, the DSP runs the program illustrated in Figure 6.

As indicated in the figure, the program is executed in two stages. Stage 1 consists of checks and initializations, while in stage 2 an endless loop is executed, waiting for new pulse data from the ADS laboratory processor or for interrupts from the XILINX device. In stage 1, a 16-bit cyclic redundancy checksum (CRC) is calculated over the entire PEROM contents to ensure the integrity of the configuration data stored there. Also, internal registers and data memory in the DSP are initialized, and the XILINX device is configured from the PEROM memory under DSP control. At the conclusion of stage 1, interrupts are enabled for receiving pulse data over the ESSI connection from the ADS laboratory processor and for responding to FIFO data requests from the XILINX FPGA.

The main program loop constantly checks to determine whether new static or dynamic pulse data have been received from the ADS laboratory processor for either the left or right sides. If so, the subroutine corresponding to the side (left or right) and type (static or dynamic) of the received data is called to fill the associated FIFO buffer allocated in DSP memory with the new data, formatting them as required by the XILINX FIFOs to generate the transmitter signals. Before dynamic data are configured for writing into a FIFO buffer, the DSP also checks to verify that enough space remains in the circular buffer to accommodate up to 22 data words, the maximum number of FIFO words resulting from the reformatting of a dynamic ESSI pulse data block.

At the end of each loop iteration, the main program checks to determine whether both the left- and right-side XILINX FIFOs are now stalled as a result of the synchronization flags being set in the left and right pulse data previously written into the FIFOs. If so, a synchronized unstall of both FIFOs is performed by writing a dedicated unstall command to the XILINX. This re-synchronizes the transmitter signals for the two sides.

The main program loop may be interrupted at any point by an ESSI receive data event or a XILINX left or right FIFO partially empty event, in which case the DSP halts the main

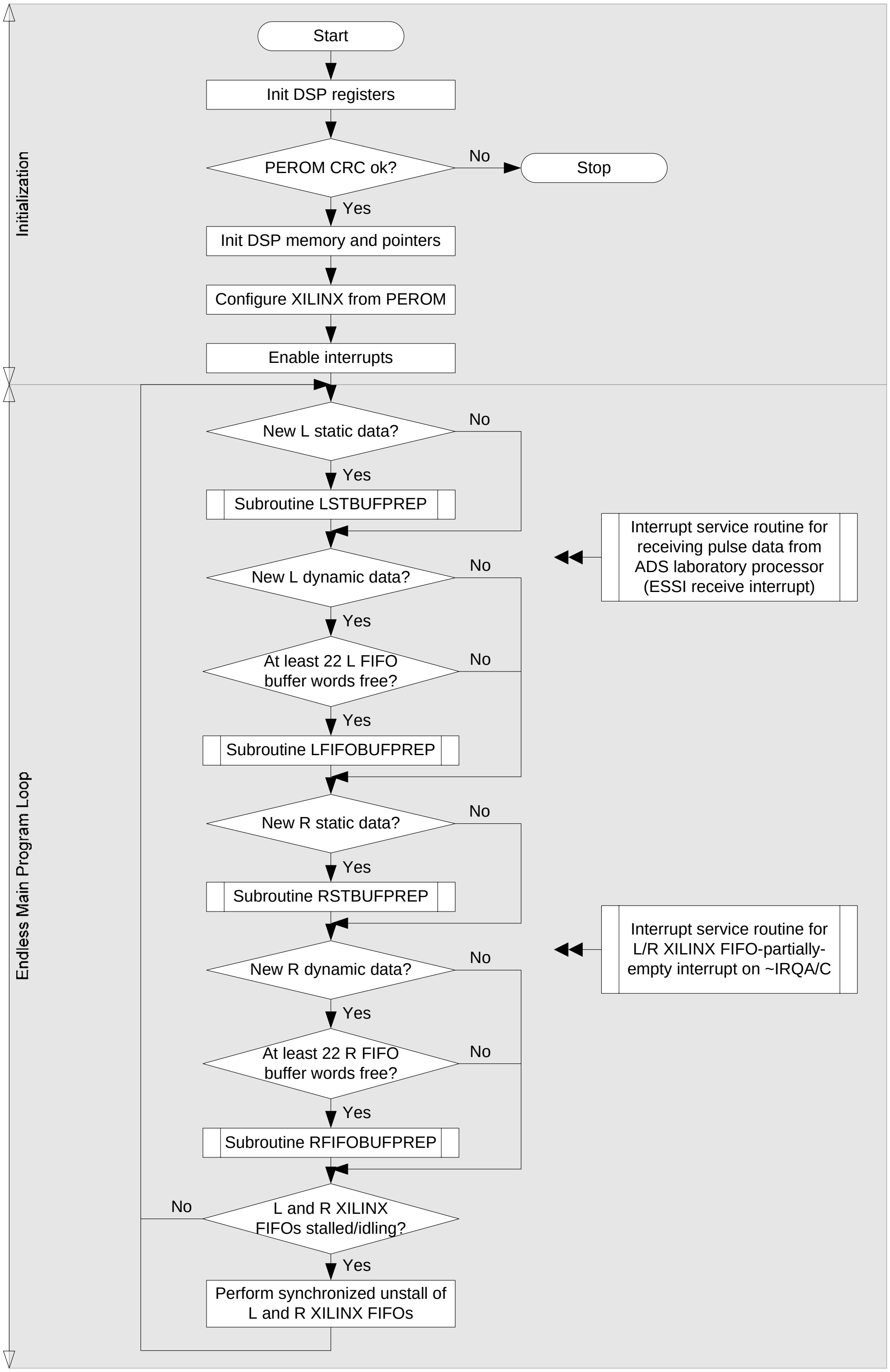


Fig. 6. Main program running in the DSP56309 after startup. The symbols L and R indicate the left and right sides, respectively. The two boxes with the double-pointed arrows on the right indicate interrupt service routines that may be invoked at any time during the execution of the main loop in the program.

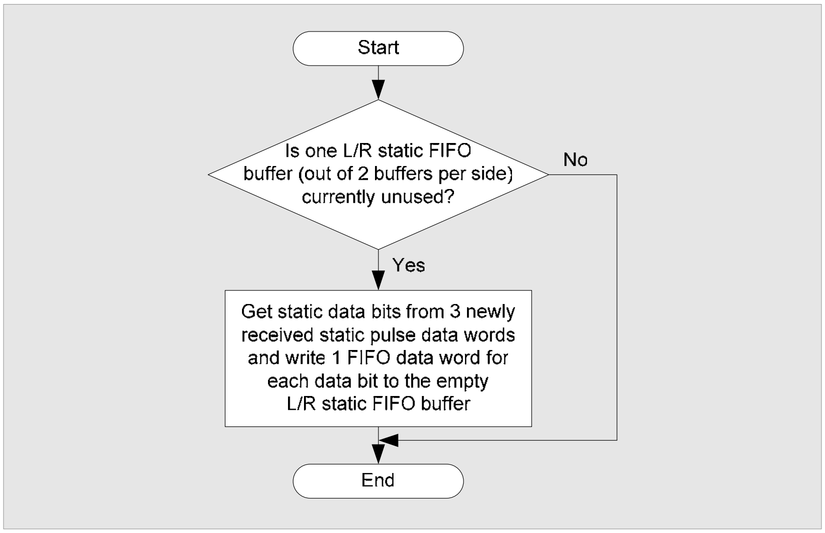


Fig. 7. Flowchart of subroutines LSTBUFPREP and RSTBUFPREP, for the preparation of FIFO data words from static pulse data for the left or right sides, respectively.

program loop to execute the corresponding interrupt service routine for storing the newly-received ADS pulse data or for transferring FIFO data to the XILINX, respectively.

Flowcharts for the various service routines called by the main program or initiated by interrupts are shown in Figures 7-10. These routines include LSTBUFPREP and RSTBUFPREP for the preparation of FIFO data words from static pulse data for the left or right sides, respectively (Figure 7); LFIFOBUFPREP and RFIFOBUFPREP for the preparation of FIFO data words from dynamic pulse data for the left or right sides, respectively (Figure 8); the ESSI interrupt routine initiated by receipt of a data word for either side (Figure 9); and the routines to replenish the partially-empty XILINX FIFOs for the left or right sides with new data (Figure 10).

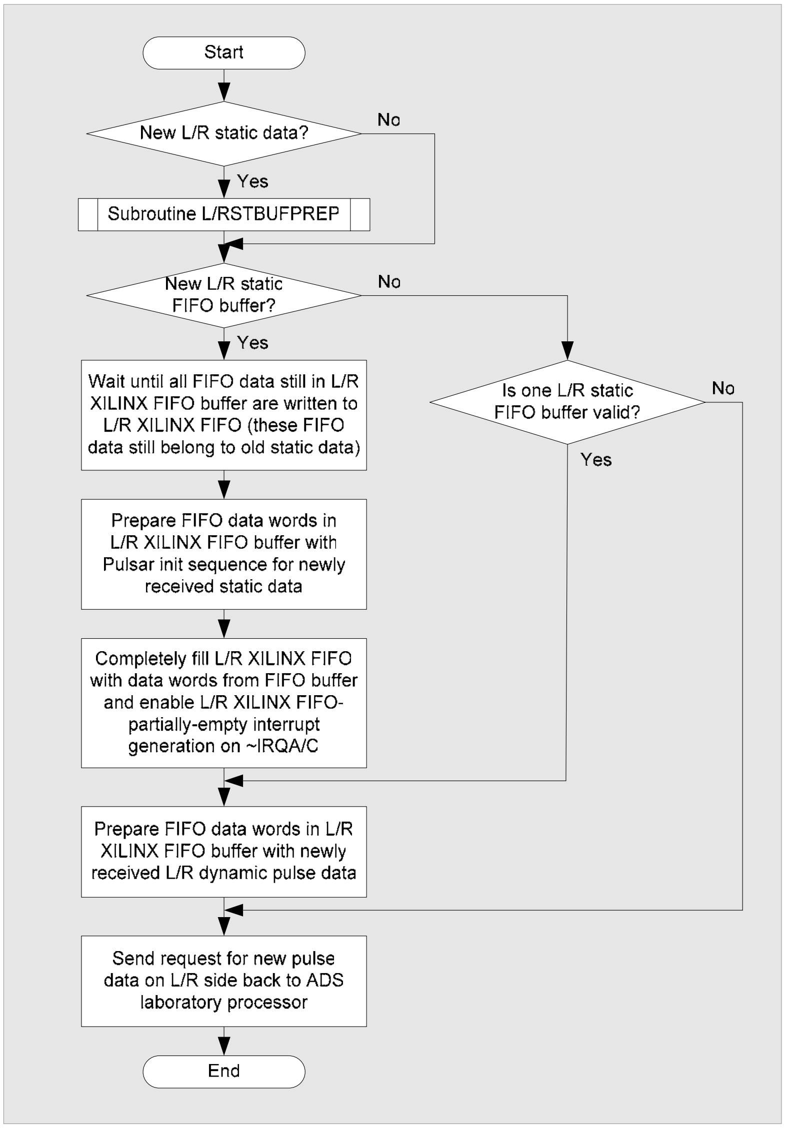


Fig. 8. Flowchart of subroutines LFIFOBUFPREP and RFIFOBUFPREP, for the preparation of FIFO data words from dynamic pulse data for the left or right sides, respectively.

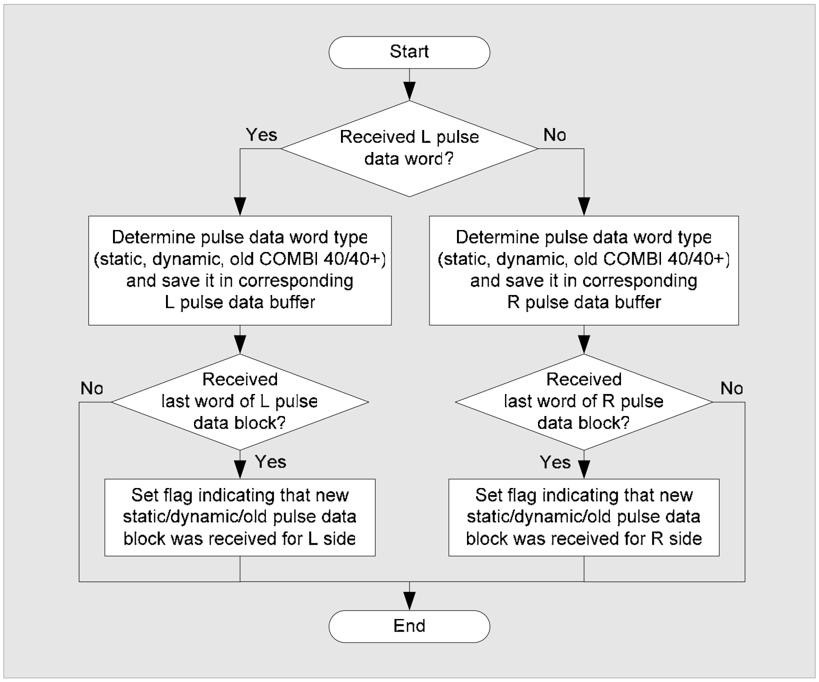


Fig. 9. Flowchart of the ESSI receive interrupt service routine executed each time a 24-bit static or dynamic pulse data word is received for left or right sides.

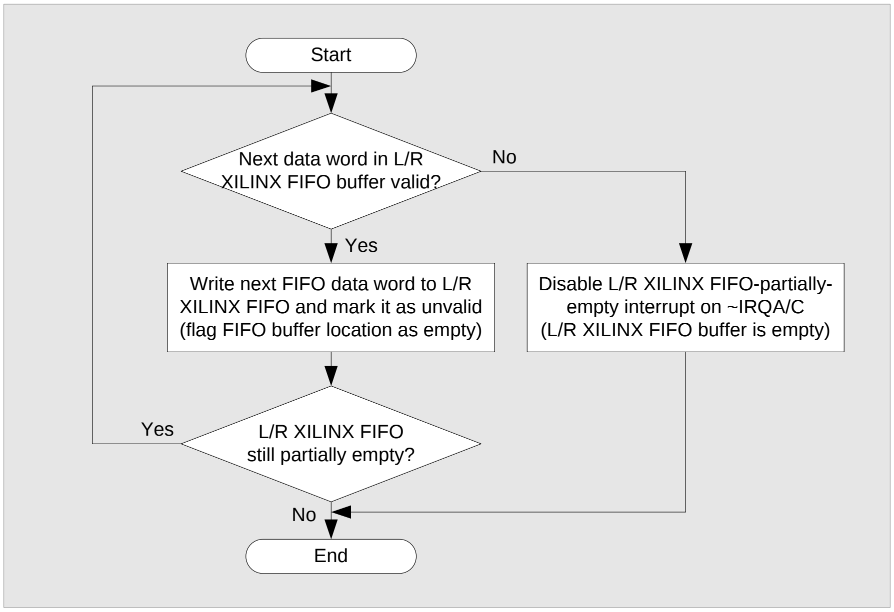


Fig. 10. Flowchart of the IRQA and IRQC interrupt service routines to replenish the partially-empty XILINX FIFOs for the left or right sides with new data.

Control of bilateral implants using the interface

Examples of laboratory control of two PULSAR implants are presented in Figures 11 and 12. The first example shows instructed generation of time-synchronous biphasic pulses at the two implants, and the second example shows instructed generation of triphasic instead of biphasic pulses, for otherwise-identical conditions. These and many other examples demonstrate the correct operation of the interface.

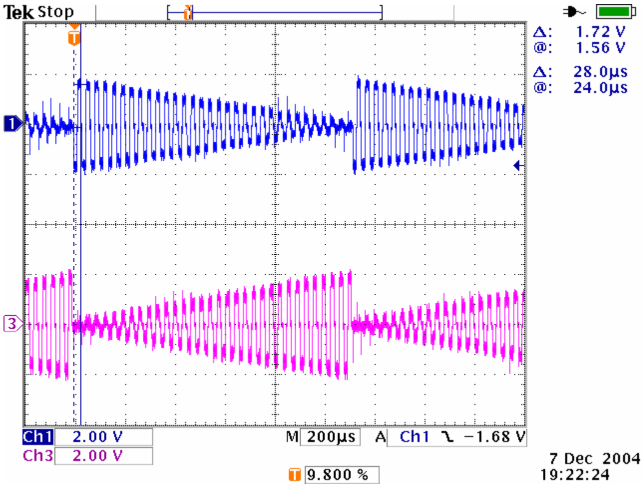


Fig. 11. Oscilloscope traces showing bilateral repetitive linear ramps of 32 simultaneous biphasic pulses each. The upper trace shows the voltage across a load resistor (to mimic the electrode impedance) at the output for electrode 2 in one PULSAR implant, and the lower trace shows the voltage across a different load resistor at the output for electrode 11 in the other PULSAR implant. Pulses are all cathodic-first biphasic with a phase duration of 14 μs and an inter-phase gap of 2.1 μs. The pulse rate at each of the dummy electrodes is 28570/s. The oscilloscope was operated in peak detect mode.

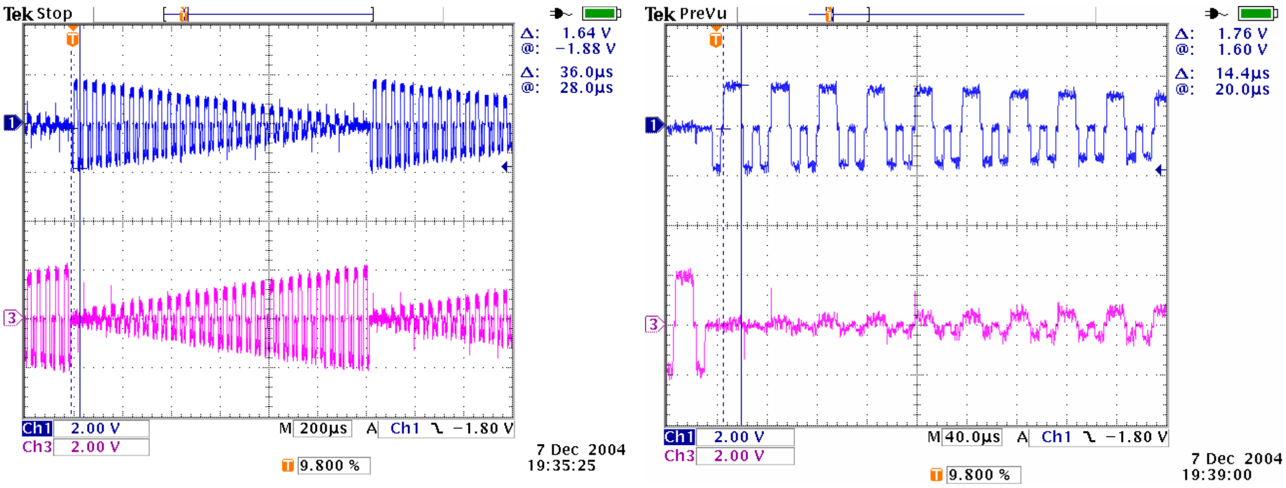
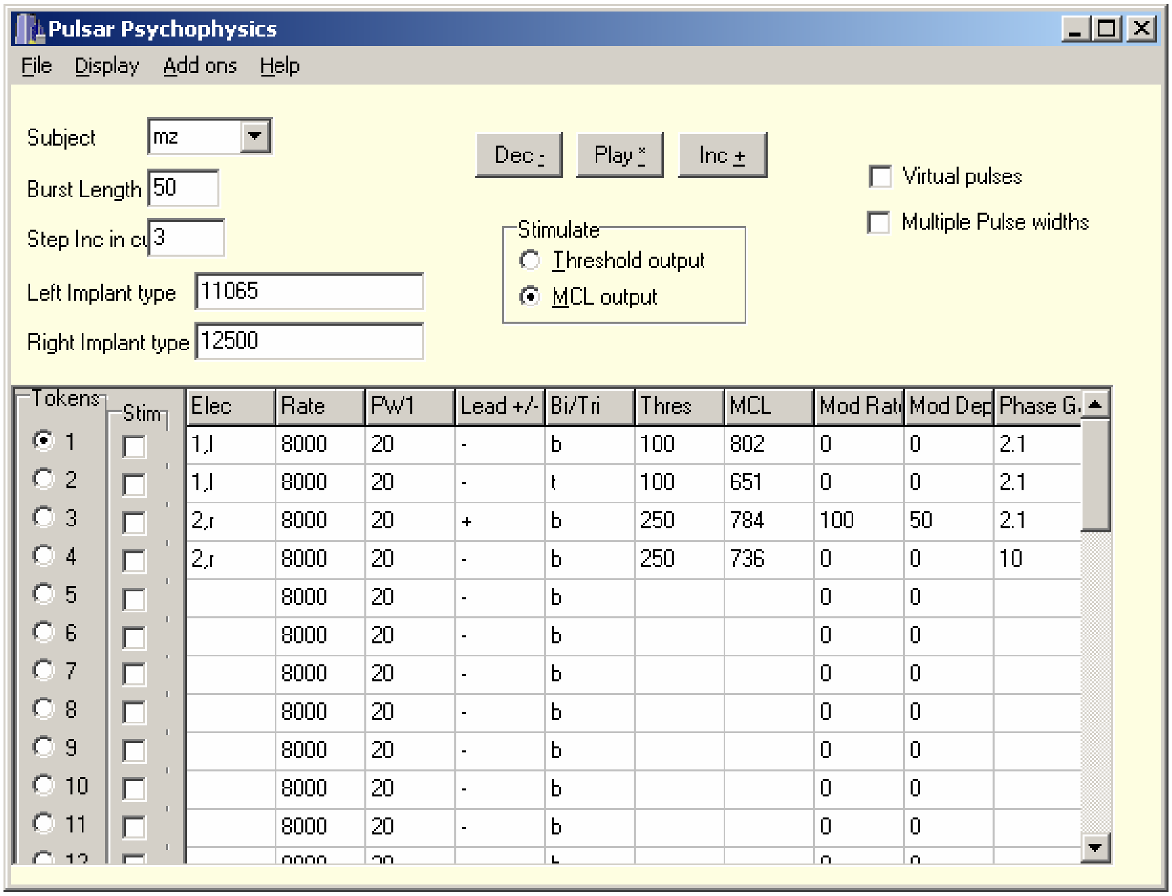


Fig. 12. Oscilloscope traces showing bilateral repetitive linear ramps of 32 simultaneous triphasic pulses each (left panel), with a zoomed-in view (right panel). The upper trace in each of the panels shows the voltage across a load resistor at the output for electrode 2 in one PULSAR implant, and the lower trace shows the voltage across a different load resistor at the output for electrode 11 in the other PULSAR implant. In this case, triphasic symmetric pulses are specified. The duration of the middle phase is 14 µs and the inter-phase gap is 2.1 µs. The pulse rate at each of the dummy electrodes is 26080/s. The oscilloscope was operated in peak detect mode.

C. Monitor program

The monitor program described in Quarterly Progress Report (QPR) 5 of the current contract (Schatzer *et al.*, 2003) has been extended to include new classes for full control of the PULSAR interface. At present, procedures have been implemented for basic psychophysical measures with recipients of PULSAR implants, such as current levels corresponding to threshold and most-comfortable-loudness (MCL) percepts. In addition, procedures have been developed for measures of sensitivities to interaural timing and amplitude differences for users of bilateral PULSAR implants, or users of a PULSAR implant on one side and a COMBI 40 or 40+ implant on the other side. Procedures for support of streaming-mode processing are in development. The extensions to the monitor program allow full access to the PULSAR interface, as described in section II.B above, and to the capabilities of the PULSAR implant, as described in section II.A above.

The basic functions of the monitor program are described in detail in Appendix 2 to QPR 5. Here we focus on the extensions to the program for supporting the PULSAR interface.



Subject mz

Burst Length 50

Step Inc in cu 3

Left Implant type 11065

Right Implant type 12500

Stimulate
○ Threshold output
● MCL output

☐ Virtual pulses

☐ Multiple Pulse widths

Tokens	Stim	Elec	Rate	PW1	Lead +/-	Bi/Tri	Thres	MCL	Mod Rat	Mod Dep	Phase G.
● 1	☐	1,l	8000	20	-	b	100	802	0	0	2.1
○ 2	☐	1,l	8000	20	-	t	100	651	0	0	2.1
○ 3	☐	2,r	8000	20	+	b	250	784	100	50	2.1
○ 4	☐	2,r	8000	20	-	b	250	736	0	0	10
○ 5	☐		8000	20	-	b			0	0	
○ 6	☐		8000	20	-	b			0	0	
○ 7	☐		8000	20	-	b			0	0	
○ 8	☐		8000	20	-	b			0	0	
○ 9	☐		8000	20	-	b			0	0	
○ 10	☐		8000	20	-	b			0	0	
○ 11	☐		8000	20	-	b			0	0	

Fig. 13. Operator (or investigator) interface in the psychophysics task of the monitor program for the PULSAR implant system. Each pulse burst definition includes specifications of electrode and implant side, pulse rate in pulses per second, phase duration in microseconds, leading phase polarity, biphasic or triphasic pulse waveform, threshold and most comfortable loudness (MCL) levels in microamperes or bit units, modulation rate in Hz, modulation depth in percent, and inter-phase gap in microseconds. The burst duration is specified separately and is constant for all pulse bursts.

Procedures for basic psychophysical measures

The procedures for basic psychophysical measures enable the operator to send pulse trains and increase or decrease the stimulus level to obtain thresholds, comfortable levels, or loud levels. The procedures also can be used for informal pitch discrimination, scaling, or matching tests, as specification of sequences of stimuli, e.g., with different rates or sent to different electrodes, is easy using the stimulus definition table in the "psychophysics window" of the monitor program (Figure 13). Up to 44 separate pulse trains can be defined in that table, which offers great flexibility in configuring tests.

Various types of pulse trains can be specified for the PULSAR interface. They include:

- Basic pulse trains where a single electrode is stimulated at a constant level and rate.
- Sinusoidally amplitude modulated (SAM) pulse trains where the operator can specify the modulation rate and depth.
- Virtual channels where two or more (typically adjacent) electrodes are stimulated simultaneously to produce a pitch percept that is different from the percept elicited with stimulation any one of the electrodes alone.
- Any of the pulse trains indicated above, but presented in conjunction with high-rate "conditioner" pulses running in the background.

Pulses in the trains are specified according to their intended waveform (biphasic or triphasic symmetric), polarity of the leading phase (anodic or cathodic), and inter-phase gap (2.1, 10.0, 20.0, or 30.0 µs). All pulses within a train share the same inter-phase gap.

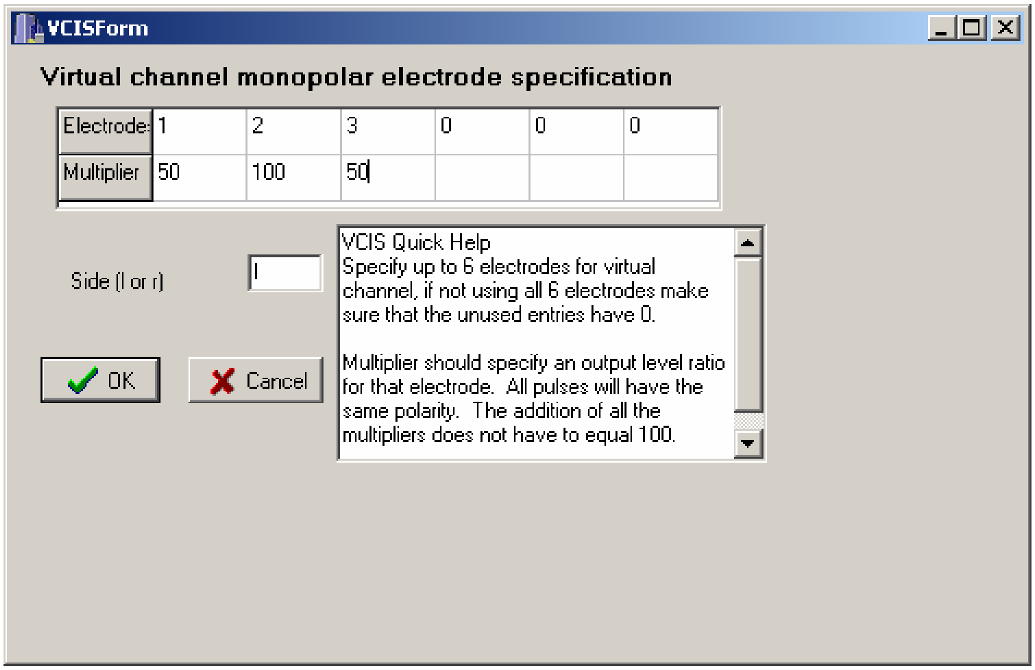
As also indicated in Figure 13, additional controls are provided for specifying the duration of the trains (in milliseconds) and for setting the step size of increments or decrements in pulse amplitude (in clinical units, cu). Once specified, trains of pulses may be presented without alteration or at higher or lower amplitudes, using the "Play," "Inc," or "Dec" buttons, respectively.

Information about the subject must also be entered prior to stimulation, including the unique identifiers for each implant. (As noted in section II.A, the identifier is included in the static data word and is required for activation of the implant.)

When the box labeled “Virtual pulses” is checked in the psychophysics window, the dialog shown in Figure 14 will pop up whenever the cursor is positioned in the electrode column of the stimulus definition table. This provides an interface for the operator to specify up to 6 electrodes and corresponding multipliers for each virtual channel.

Conditioner pulses also may be specified with the extended monitor program. This was not possible with the prior Med El COMBI 40 and COMBI 40+ implants, as those implants are not capable of supporting the high rates required for conditioner pulses, generally 3000 pulses/s or higher (Rubinstein et al., 1999; Hong et al., 2003). The PULSAR implant supports such rates, and allows evaluation of the efficacy of conditioner pulses presented either simultaneously or sequentially across specified electrodes.

A separate window, shown in Figure 15, is used for the specification of conditioner stimuli. The operator can go back and forth between the psychophysics and conditioner windows as needed. In the conditioner window, up to 12 electrodes can be selected to receive conditioner pulses. The amplitude of the pulses also is specified for each of the selected electrodes. The pulses may be presented simultaneously or sequentially across the selected electrodes, as noted above. The waveform of conditioner pulses is constant across the electrodes within an implant. However, a different waveform may be specified for the contralateral implant, for users of bilateral PULSAR implants. For such users,



Virtual channel monopolar electrode specification

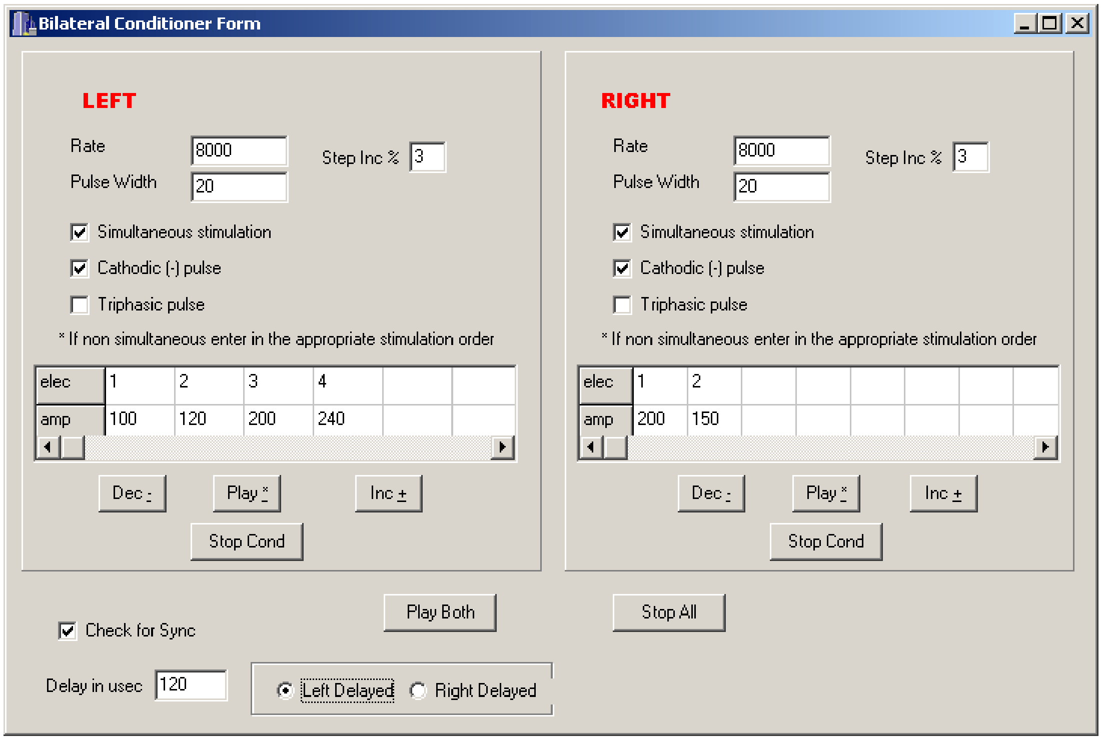
Electrode	1	2	3	0	0	0
Multiplier	50	100	50			

Side (l or r): l

VCIS Quick Help
Specify up to 6 electrodes for virtual channel, if not using all 6 electrodes make sure that the unused entries have 0.

Multiplier should specify an output level ratio for that electrode. All pulses will have the same polarity. The addition of all the multipliers does not have to equal 100.

Fig. 14. Window for the specification of virtual channels in the monitor program.



LEFT

Rate: 8000
Pulse Width: 20
Step Inc %: 3

☑ Simultaneous stimulation
☑ Cathodic (-) pulse
☐ Triphasic pulse

* If non simultaneous enter in the appropriate stimulation order

elec	1	2	3	4		
amp	100	120	200	240		

RIGHT

Rate: 8000
Pulse Width: 20
Step Inc %: 3

☑ Simultaneous stimulation
☑ Cathodic (-) pulse
☐ Triphasic pulse

* If non simultaneous enter in the appropriate stimulation order

elec	1	2						
amp	200	150						

☑ Check for Sync

Delay in usec: 120

● Left Delayed ○ Right Delayed

Fig. 15. Window for the specification of conditioner pulses in the monitor program.

delivery of conditioner pulses on one side also may delayed with respect to delivery on the other side. Conditioner pulses also can be presented synchronously across the two sides.

Rates of conditioner pulses may be specified up to the maximum supported by the implant and also independently across the two sides for users of bilateral implants. As indicated in Table 1, that maximum rate declines as the number of addressed electrodes is increased.

Conditioner pulses can be presented in isolation for either the left, right, or both implants, or in conjunction with "deterministic" stimuli, as specified in the psychophysics window. Conditioner pulses are presented continuously until stopped with the "Stop Cond" buttons for the left or right implants, or with the "Stop All" button for both implants, in the conditioner window (Figure 15). Deterministic stimuli may be presented in conjunction with ongoing conditioner stimuli at any time using the psychophysics window.

Deterministic and conditioner stimuli may share electrodes. In instances where the presentation of conditioner pulses needs to be stopped and restarted, the conditioner stimuli are activated for a minimum period of three hundred milliseconds prior to any presentation of deterministic stimuli. This provides at least some opportunity for the subject to adapt to the conditioner stimuli.

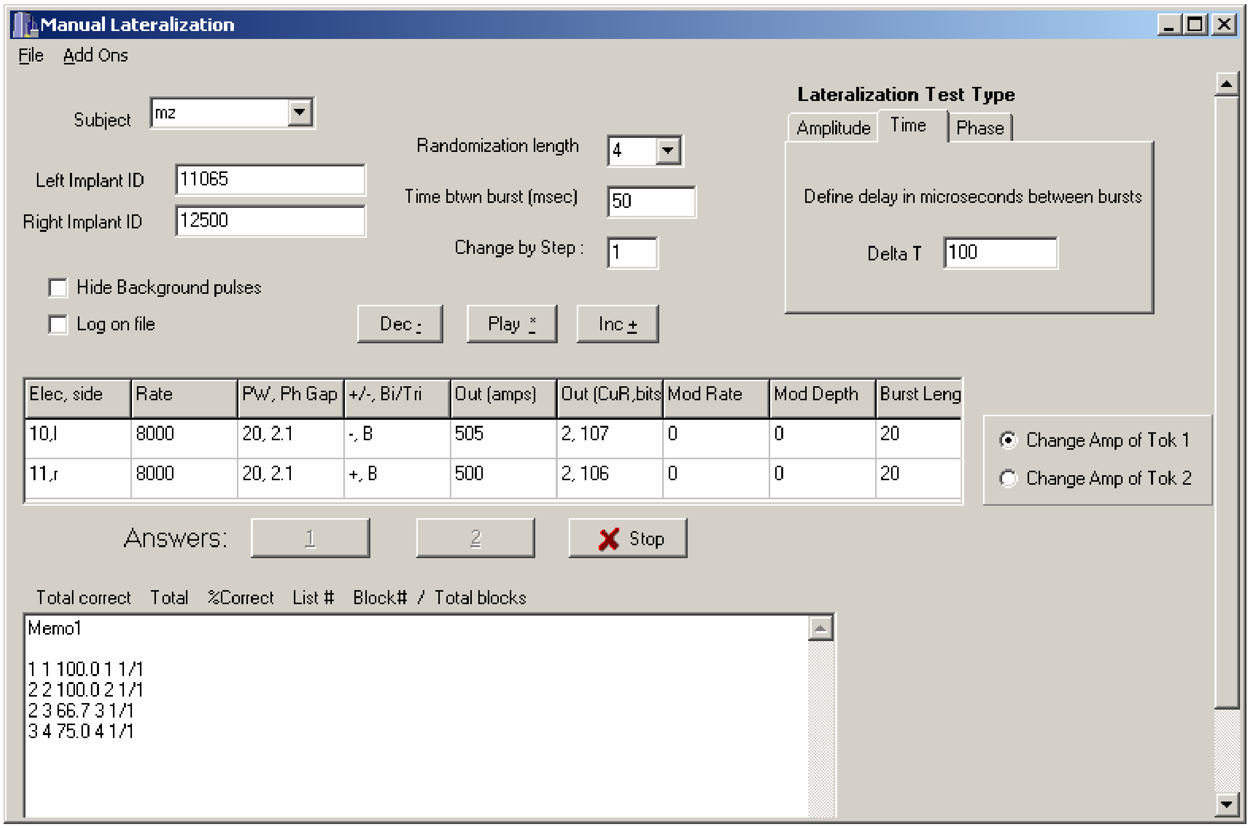
The conditioner and deterministic stimuli may be specified within certain limits, principally to eliminate possibilities for contentions or asynchronies that otherwise might occur for shared electrodes. Those limits include the following:

- Pulse duration – if conditioner and deterministic pulses share an electrode, their pulse durations may be different, but the longer pulse duration is limited to the durations achieved through a dynamic phase extension of the shorter pulse duration. That is, the longer pulse duration can be defined in percentage steps of 125, 150, 175, and 200% of the shorter pulse duration – typically the conditioner pulse duration.
- Rate – the deterministic rate must be a sub multiple of the conditioner rate.
- Inter-phase gap – conditioner and deterministic pulses must have the same inter-phase gap.

The new procedures for psychophysical tests support an exceptionally wide range of stimuli and utilize most of the capabilities of the PULSAR implant. In addition, conditioner stimuli may be specified and applied, in isolation or in conjunction with other stimuli.

Lateralization tests

Tests to measure lateralization abilities for users of bilateral PULSAR implants are configured and administered through use of a "lateralization" window, shown in Figure 16. This window is similar to the one used for other implant systems, but includes controls for the specification of parameters that are unique to the PULSAR implant. The



Subject: mz

Left Implant ID: 11065

Right Implant ID: 12500

☐ Hide Background pulses

☐ Log on file

Randomization length: 4

Time btwn burst (msec): 50

Change by Step : 1

Lateralization Test Type

Define delay in microseconds between bursts

Delta T: 100

Elec, side	Rate	PW, Ph Gap	+/-, Bi/Tri	Out (amps)	Out (CuR,bits	Mod Rate	Mod Depth	Burst Leng
10,l	8000	20, 2.1	-, B	505	2, 107	0	0	20
11,r	8000	20, 2.1	+, B	500	2, 106	0	0	20

● Change Amp of Tok 1

○ Change Amp of Tok 2

Total correct Total %Correct List # Block# / Total blocks

```
Memo1

1 1 100.0 1 1/1
2 2 100.0 2 1/1
2 3 66.7 3 1/1
3 4 75.0 4 1/1
```

Fig. 16. Lateralization test window for the PULSAR interface in the monitor program.

bilateral stimuli are specified in a stimulus definition table within the lateralization window. Specification of the stimuli includes the following:

- Electrode and side if using single-electrode bursts. If using virtual channels, up to 6 electrodes are defined together with a multiplier and side of stimulation. The multiplier refers to the percentage of the defined output pulse amplitude to be stimulated on the particular electrode.
- Rate – normally this is the same rate for both electrodes, but the operator has the ability to specify any rate possible with the implant and pulse duration specified.
- Pulse duration and inter-phase gap.
- Phase polarity and pulse waveform.
- Output amplitude specified in either microamperes or bit units.
- Modulation rate (in Hz) and depth of modulation (in percent) can be defined for a SAM pulse train or are each set to zero for a test with unmodulated pulse trains. SAM pulse trains begin at the minimum modulation amplitude (phase 0), unless otherwise specified in the phase tab of the lateralization test type box.
- Burst length is specified in milliseconds and defines the length of one pulse train. During one presentation the pulse train is generated 3 times with a delay between bursts in milliseconds as specified in the corresponding edit-box.

The stimuli presented bilaterally can be any of the pulse trains defined in the psychophysics window. With the PULSAR interface, possible effects of conditioners, high rates, virtual channels and pulse waveform on lateralization abilities can be studied, in addition to possible effects of differences in the timing or amplitude of the stimuli on the two sides. The operator can define the conditioners just as in the procedures for basic psychophysical measures and go back and forth between windows, changing the conditioners as desired. Once conditioner pulses are enabled, they run continuously in the background so that the subject can adapt to them and so that the "deterministic" stimuli are presented in the context of a continuous background of conditioner pulses and their possible effects on discharge activities within and among auditory neurons.

Three different tests can be administered from the lateralization window, as indicated in the top right corner of Figure 16. These tests include measures of sensitivity to interaural timing or amplitude differences between pulses across the two sides, and, for SAM pulse trains, differences in the phase of the modulation waveform across the two sides. These tests also are supported for other implant systems, and are described in detail in Appendix 2 of QPR 5.

D. References

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III. Plans for the next quarter

Among the activities planned for the next quarter are:

- Continuing studies with recipients of the Nucleus Contour Electrode array with percutaneous access.
- Implementation of software tools for the bilateral Med-El PULSARCI^{100} interface to support the generation of stimulation pulse waveforms that were pre-processed off-line, providing a platform for the study of more advanced signal processing strategies.
- A two-week visit by the first Med-El PULSARCI^{100} subject, ME-25, from Germany, February 21 through March 4, 2005.
- Distinguished Guest address by Blake Wilson to the faculty and the families of implanted children for the annual Nalli Day, The Hospital for Sick Children, Toronto, Canada, February 16, 2005.
- Grand Rounds presentation by Blake Wilson to the Department of Otolaryngology, University of Toronto, Toronto, Canada, February 17, 2005.
- A trip to India by Blake Wilson to meet with Mr. Rangasayee, Director of the Ali Yavar National Institute for the Hearing Handicapped in Mumbai, and to participate in a conference organized by him to bring together the principal people in India with a keen interest in the remediation of hearing loss in the country, March 2005.

IV. Acknowledgments

We thank volunteer research subjects NP-6, NP-8, and NP-9 for their participation in studies conducted during this quarter.

Appendix 1: Announcements and summary of reporting activity for this quarter

Lianne Cartee will be leaving the RTI team in January 2005, to teach and become an Associate Professor at North Carolina State University in Raleigh. She has made many important contributions to this and prior projects in the "speech processors" series at RTI. We will miss her and wish her all the best in her new endeavors.

We are pleased to note that Blake Wilson was a Guest of Honor at the *5th Wullstein Symposium on Bilateral Cochlear Implants and Binaural Signal Processing*, held in Würzburg, Germany, December 2-6, 2004.

Wilson also was designated as a "Friend Forever" to the International Center of Hearing and Speech in Kajetany (near Warsaw), Poland, on October 14, 2004. He has served as a member of the International Scientific Board for the Center since early 2003, and will continue that service for the foreseeable future.

Blake Wilson was a co-organizer with Peter Roland of the *Hearing Preservation Workshop III*, held at the University of Texas Southwestern Medical Center at Dallas, October 15-17, 2004. Details about the workshop, including the program, are presented at http://www.hearingpreservation.com/.

Reporting activity during the past quarter included the following:

Publications

Wilson BS, Sun X, Schatzer R, Wolford RD: Representation of fine structure or fine frequency information with cochlear implants. Int Cong Ser 1273: 3-6, 2004.

Invited Presentations

Wilson BS, Wolford RD, Lawson DT, Schatzer R, Sun X: Update on EAS studies at the Research Triangle Institute. *Hearing Preservation Workshop III*, Dallas, TX, October 15-17.

Wilson BS, Cartee LA, Cox JH, Lawson DT, Schatzer R, Sun X, Wolford RD: The auditory prosthesis as a paradigm for successful neural interfaces. *Neural Interfaces Workshop*, National Institutes of Health, Bethesda, MD, November 15-17.

Wilson BS, Wolford RD, Brill S, Lawson DT, Schatzer R: Speech coding for bilateral cochlear implants. *5th Wullstein Symposium on Bilateral Cochlear Implants and Binaural Signal Processing*, Würzburg, Germany, December 2-6.

Chaired Sessions

Wilson BS: Session on Neural Enhancement. *Hearing Preservation Workshop III*, Dallas, TX, October 15-17.

Appendix 2: Further development of the streaming mode tools

In Quarterly Progress Report (QPR) 5 for the current contract, we introduced the streaming mode as a collection of software tools for our speech laboratory system that provides an efficient, fast and flexible approach to implementing and evaluating new and relatively complex speech processor designs. In this mode, pre-processed stimulation sequences are delivered to the test subject's implant(s) under operator control through our Windows-based monitor program. The stimulation sequences are generated off-line in the MATLAB programming environment by processing speech tokens such as sentences or consonants in digital audio file format, or music and melody recordings, and converting them into a stimulation pulse sequence, according to a given processing strategy also implemented in MATLAB. The powerful and highly flexible MATLAB environment greatly facilitates the development and subsequent testing of complicated processing strategies. Such strategies usually can be implemented for real-time execution, using DSP hardware and software, if they show sufficient promise in the initial (streaming mode) tests to justify the high expense of this additional step.

The monitor program provides procedures in streaming mode for the administration of tests of speech and melody identification or recognition. The procedures control the delivery of processed tokens to the implant via the streaming mode of operation, and the procedures prompt the subject for responses following each delivery. Subject responses are recorded.

The speech tests include the identification of 16 or 24 consonants, in a vowel-consonant-vowel context, and recognition of sentences, including the CUNY sentences among others for English-speaking subjects and the Oldenburger sentences for German-speaking subjects. The tests of melody recognition can be tailored to include melodies that are familiar to the subject, e.g., Polish folk tunes for Polish subjects.

In this Appendix we briefly describe the tools we have developed for administration of the melody tests, under control of an augmented monitor program. Tools for the administration of the speech tests were described in QPR 5.

In addition, we describe new extensions to the monitor program that allow dynamic control of pulse parameters and stimulus sites, from one pulse to the next. This new capability can be used to implement advanced speech processor designs, such as designs using virtual channels to represent "fine structure" or "fine frequency" information with cochlear implants, as mentioned in QPR 8 for this contract and as described more fully in Wilson et al., 2004.

The tools developed to date apply to implant systems with percutaneous connectors. Work is underway to extend the tools for use with the new interface for control of PULSAR$_{\text{CI}}{}^{100}$ implants, as mentioned in the main body of this report.

Dynamic control of pulse parameters and stimulus sites

Recently, the streaming mode tools as described in QPR 5 have been extended to support a more general paradigm of specifying pre-processed stimulation sequences. In the initial implementation, the stimulation sequence derived from a digital audio token in MATLAB consisted of a sequence of pulse amplitude values only. All other information on stimulation parameters, such as electrodes, pulse width, rate and order of stimulation pulses was static and identical for all pre-processed pulse sequence files for a given processor configuration.

With the latest modifications of the streaming mode, in addition to the pulse amplitude values, an electrode or more generally a stimulation site address is stored as dynamic information in the pre-processed data sequence as well. Also, 6 bits of dynamic information are reserved for future use, such as for a dynamic pulse width or pulse gap extension. These modifications lift the restriction of a static and pre-determined stimulation order across electrodes. With the dynamic stimulation site address stored in conjunction with each amplitude value in the pre-processed stimulation sequence, it is now possible to dynamically direct a processor channel output to any one of a set of pre-defined intracochlear stimulation sites. Such a stimulation site can be a single electrode, or a combination of two or more electrodes targeted by simultaneous stimulation pulses, thus combining to form a virtual stimulation channel. For detailed discussions of virtual channels and their use, see QPR 7 for the current project and Wilson et al., 1994. With dynamic assignments of channel outputs to stimulation sites, *n*-of-*m* (spectral peak picking) strategies also can be implemented. Another interesting possibility is one mentioned above, to represent instantaneous frequencies in a band through fine-grained and dynamic adjustment of stimulus sites (or centroids of neural excitation patterns, as may be controlled through virtual channels).

Melody recognition test

The monitor program has been extended to include administration of melody recognition tests in the streaming mode. The extension mimics the test procedure described in QPR 10 (Lawson et al., 2004). In this case, however, melodies are processed off-line using MATLAB programs and the processed items are sent to the implant via the streaming mode and under the control of the extended monitor program. Previously, input melodies were processed in real time, either with the DSP-based laboratory processor or with the subject's own clinical processor. The advantage of the streaming mode and associated off-line processing is that complex strategies can be implemented and tested at a relatively low cost, as noted above.

The parameters of a melody test are stored in a file named "streamplan." This file is populated prior to the administration of the test. Use of the streamplan file by the monitor program is described in QPR 5. The file for melody tests includes an identifier, melnnll, in which nn is the number of notes per melody and ll is the list number that references titles of the melodies to be included in a particular test. The file also contains information about whether the test is to be conducted in quiet or with background noise, and whether the right, left or both implants are to be used. The file is built with a command such as the one below:

```
MZ, C:\specfiles\dualci24pec.txt, C:\streamfiles\melfiles, 0, L, mel1601
```

In this example, the test administered by the monitor program will be conducted in quiet, with stimulation of the left implant only. The test will present melodies generated with 16 notes each and it will use the melodytitle01 file for the text on the melody recognition test buttons.

Up to 20 melodies can be loaded for one test. The window display is quite similar to the real-time version and can be executed for a practice or a test setting. In a practice setting, melodies can be played in any order by clicking the corresponding buttons. An example of a display for a test or practice run that includes 12 melodies is shown in Fig. A2.1.

After each test, the monitor program creates an entry to the subject's melody data archive file, that can then be viewed and analyzed using the melANAL.exe utility program described in QPR 10.

Fig. A2.1. User interface for melody recognition tests.

References

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