Using Virtual Instrumentation to Develop a Modern Biomedical Engineering Laboratory*

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This paper describes the development of a variety of classical biomedical experiments, particularly for use in a teaching laboratory. Several lab projects are described covering topics from basic electrophysiology to cardiovascular hemodynamics. The common thread through all of these experiments is their PC-based nature, all of them being automated using LabVIEW™ or BioBench™ software from National Instruments. The exercises depicted are intended to introduce students to fundamental concepts of biomedical experimentation, from the instrumentation and data acquisition requirements to subsequent data analysis techniques. Each project has a basic analysis section that effectively demonstrates physiological properties pertinent to the respective studies as well as an advanced analysis section that explores potential research topics relevant to the experiments. The lab experiments are designed to interactively teach some of the fundamental theories associated with each field. This not only reinforces basic knowledge, but also trains students in the application of these theories to laboratory research.

INTRODUCTION

THIS PAPER is intended to portray the use of LabVIEW™ in the education of engineering students interested in biomedical research and applications. In particular, it is focused on the recent development of our Biomedical Systems and Instrumentation Laboratory (BSIL) at Rice University. The exercises discussed are intended to introduce students to fundamental concepts of biomedical experimentation, from the instrumentation and data acquisition requirements to subsequent data analysis techniques. The fields of study currently being emphasized include topics such as electroneurology, cardiac electrophysiology, and cardiovascular hemodynamics. Each project consists of a set of experiments exemplifying the types of studies that are typical in each field. This paper serves as an overview of these endeavors. Emphasis is placed on a representative experiment in the neural electrophysiology area for the purpose of detailing programming techniques and other pertinent issues.

Our lab exercises are all designed as PC-based experiments. They are controlled via original virtual instruments (VIs) developed with the LabVIEW programming environment or by using BioBench software. (LabVIEW and BioBench are both products of National Instruments, Austin, TX.) Due to the modular nature of the LabVIEW software being used, many of the programs discussed in this paper can be readily adapted to similar studies that other instructors/institutions may be more interested in pursuing.

Using LabVIEW to facilitate the data generation and collection changes the educational focus from learning to use the equipment to learning the conceptual objectives presented in the lab. At the same time, this allows the students are exposed to equipment requirements and gain a basic to understanding of data acquisition techniques. Thus, these labs allow the students to learn the concepts of the phenomena first, and second, to learn the measurement system.

BSIL LABORATORY DESCRIPTION

The development of a new laboratory involves significant planning and resources. Specialized instrumentation and equipment needs are often paramount, yet expensive and special purpose. With the Rice BSIL, this dichotomy led directly to the use of PC-based LabVIEW workstations as the foundation for the lab development [1]. The 'G' programming environment, upon which LabVIEW is based, lends itself to the creation of 'virtual instruments' that can mimic or expand upon the functions of specialized commercial equipment, and thus serve a more general-purpose rule in providing instrumentation and equipment support.

The advantages of using such a general-purpose data acquisition scheme are numerous. Foremost

* Accepted 9 September 1999.

is the flexibility to perform a wide variety of experiments under the auspices of a single workstation. Startup time and training required by lab personnel and students alike is also reduced, as are capital expenses, particularly when compared to multiple purchases of specialized equipment. As a programming environment, LabVIEW also provides a platform for advanced data analysis techniques from digital signal processing to regression analysis.

Thus, the BSIL has evolved as a modern PC-based biomedical data acquisition and analysis laboratory. It encompasses a tutorial quality in which fundamental physiological properties can be routinely demonstrated as well as a research-quality platform for more advanced endeavors.

The lab workstation

The standard workstation used for the lab projects described herein is illustrated in Fig. 1. It includes a 333 MHz Pentium computer with an internal data acquisition (DAQ) board. The 12-bit PCI-MIO-16E-4 from National Instruments (NI) has worked well for all of the labs in this paper. An NI Signal Conditioning eXtensions for Instrumentation (SCXI) system is also included to perform much of the signal conditioning required, particularly when dealing with very small voltage recordings. The SCXI-100 chassis houses an SCXI-1100 32-channel differential input multiplexer module, an SCXI-1120 8-channel isolated input module, and an SCXI-1180 feed-through panel. The SCXI-1100 and SCXI-1120 are used to condition input signals while the SCXI-1180 allows for simultaneous output from the DAQ board (used as a stimulator for the various preps). The SCXI-1100 and SCXI-1120 modules require some specific setup to be compatible with the labs given in this manual. The only physical setup that is required for the SCXI-1100 module is to set the filters as desired for the experiment at hand. The filter/gain settings for the SCXI-1120 module will vary depending on the lab being conducted. The SCXI-1120 module has an SCXI-1305 BNC interface to allow for easy reconfiguration and provide AC coupling as required.

Secondary to the lab workstation is a mobile workstation consisting of a 266 MHz laptop with a DAQCard-AI-16E-4 PCMCIA card. Combined with the SCXI chassis, our experimental capability becomes portable, allowing experiments to be conducted at a variety of hospitals in the nearby Houston Medical Center. (Note: experiments using stimulus output also require an external stimulator in the mobile configuration since the DAQCard does not have analog output capability. Stimulus output can still be triggered digitally.)

Generic instrumentation/data acquisition issues

With the setup described above, a number of issues had to be addressed. As in any experimental research, the calibration of the equipment being used is of utmost importance. These experiments are no different. In the nerve electrophysiology lab, significant amplification can be required depending on the particular experiment. It is therefore necessary to properly calibrate the electrodes and and data acquisition system. If possible, the system should be calibrated with the calibrator in series with the recordings, so as to account for electrode and junction resistances, and other interference phenomena [2]. The system should be calibrated prior to each trial series, and the calibration coefficients should always be saved with the data.

Our electrophysiology studies involved several technical issues that needed resolution. One was the frequency response of the input amplifiers. A

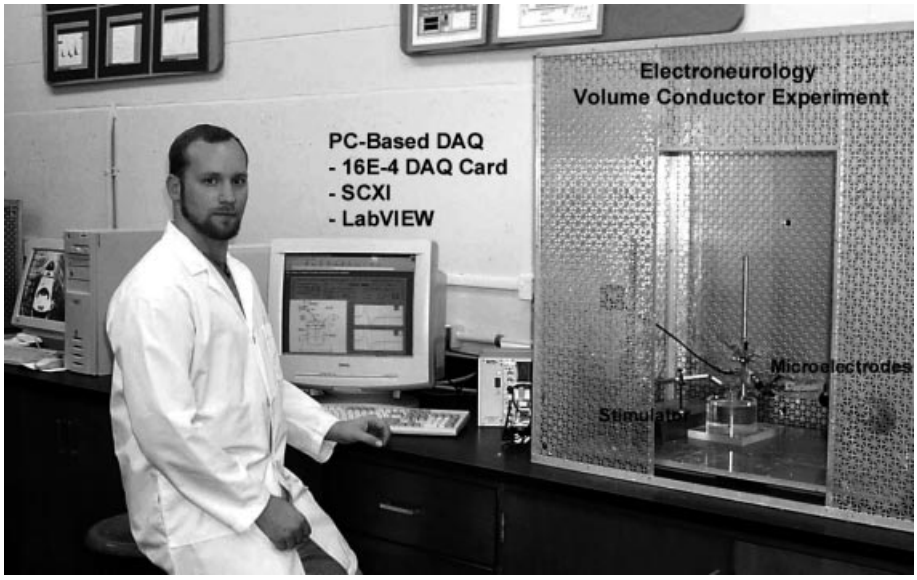

Fig. 1. Typical biomedical systems and instrumentation laboratory workstation. It is shown here configured for an experiment demonstrating the effects of a volume conductor on electroneurology recordings.

frequency response VI was developed using simultaneous I/O to test the SCXI/DAQ amplifiers. (Note: for assessment of frequency response at higher gains, the computer-generated output signal had to first be attenuated (by a voltage divider) prior to passing it to the SCXI/DAQ amplifiers in order to prevent the amplifiers from being saturated. If high value resistors were chosen in implementing the voltage divider, the frequency response of the amplifier would be altered due to altered input impedance. Using 10 kΩ and 1 MΩ resistors for a 10^2 division worked well for this case.) The frequency response so examined was found to be flat to 10 kHz (maximum tested) for all gain settings. An independent Fourier analysis (via FFT) was conducted on an oversampled (50 kHz) nerve compound action potential (CAP), which indicated that there were no significant frequency components above 6 kHz. Therefore, the frequency response of the amplifiers was considered adequate to provide appropriate gain even for the higher frequency components of a nerve GAP.

Another issue with the amplification is voltage offset. The common mode voltage rejection of the SCXI-1120 is excellent, but problems can be encountered if the steady potential difference between the recording electrodes and ground is relatively large (e.g. 300 mV). In such a case, amplification by a factor of 20 would saturate the SCXI-1120 output (±5 V). Usually, CAPs are recorded using AC coupling in order to filter out any DC offset. The SCXI-1304 and SCXI-1305 terminal boards have AC coupling capability onboard with a fixed lower frequency cutoff level of 0.167 Hz. This is sufficient for nerve electrophysiology studies, but should be reviewed for different biomedical research applications.

Recording electrical signals in the microvolt (μV) to millivolt (mV) range may also require additional measures to obtain data of sufficient quality. All physical instruments related to the data collection should be referenced to a single well-established ground reference (this is called a 'star' type connection). This precaution, one ground and one connection to that ground from each piece of equipment, eliminates the presence of ground loops, which can induced oscillations and corrupt the signals being acquired. When dealing with very small signals in the μV range, it is often necessary to use cumulative averaging (N trials) where the signal-to-noise ratio is improved by $\sqrt{N}$. This type of automated averaging routine is included in some of the VIs that have been developed.

Having addressed some of the generic issues fundamental to this type of laboratory setup, the focus could then be directed towards the design and implementation of individual experiments.

EXPERIMENT DESCRIPTION

As outlined previously, a wide array of experiments are in development for use in our Biomedical Systems and Instrumentation Laboratory. The following sections provide a cursory look at these ongoing endeavors. Detailed information regarding the electrophysiology experiments will be supplied to enable readers to use and/or modify the `NrvSD` VI and its sub-VIs, which are included on the accompanying CD-ROM.

Whereas generic issues and references to additional capabilities are made throughout this paper, only a representative sample of VIs will be included on the accompanying CD-ROM. Other references and capabilities however, will eventually be made available via the Courseware segment of the National Instruments website (www.natinst.com).

Electroneurology

Vertebrate neurons consist of cell bodies, long fiber-like processes called axons, and specialized nerve terminal endings called synapses. Individual nerve fibers are gathered together in nerve trunks or simply nerves. Neurons are responsible for a remarkable variety of communication functions, including delivery of sensory information to the brain, mediating local reflexes, and autonomic functions such as control of heart rate, breathing, and visceral function. Neurons also control muscle function, which is the focus of the neuromuscular electrophysiology labs. The frog sciatic nerve bundle is often used as the prototypical nerve preparation, and it has historically served as one of the most useful models for learning the properties of nerve conduction.

The objectives of these laboratories incorporate fundamental and animal preparation and data acquisition techniques in addition to the study of specific physiological phenomena. The properties of vertebrate (frog) nerve axon bundles that are studied include recruitment, excitability (strength/duration relationship), conduction velocity, and refractory period. Neuromuscular studies include recruitment, isometric/isotonic contractions, tetany, and treppe (also called the 'staircase' phenomenon for the initial increase and subsequent decrease in CAP amplitude during repetitive stimulus application). The excitability properties of nerves are addressed in greater detail below.

Experimental setup

The primary nerve studies are performed on an isolated frog nerve preparation established by mounting a nerve segment across a parallel array of electrodes in a moistened plexiglass chamber. Compound action potentials (CAPs) thus recorded are expected to be in the 1–10 mV range and therefore require some amplification to provide an input signal that covers the input dynamic range of the analog to digital (A/D) converter. Performing these studies *in vivo* (i.e. nerve situated within the leg but recording made from the surface of the leg), or with the nerve encased in another type of conducting medium results in field potential recordings of the order of 10 μV. In this case, a

gain of 10^5 is typically necessary to boost the signal into the ± 5 V dynamic range of the A/D converter. This can be accomplished using an amplifier with high input impedance (>10 MΩ) and excellent common mode rejection properties (CMRR = 100 dB). As discussed previously, amplifier bandwidth should be flat to 10 kHz. Cumulative averaging is usually required to pull the small signal out of its noisy environment.

The PC/DAQ setup described earlier was used to prototype these experiments. The data acquisition board was used to trigger the stimulation pulses and record the data from each electrode with the SCXI interface performing the required signal preconditioning. The SCXI-1120 provided isolation amplifiers with individual gains of up to 2000 and 10 kHz filters for 8 differential input channels. The DAQ board added a maximum gain of 100, for a total possible gain of 2×10^5. The SCXI-1180 feedthrough panel enabled the analog output of the DAQ board to be used as the stimulus.

Generic VI development

The VIs for the neutral lab all require simultaneous I/O to stimulate the nerve preparation and record from it. To that end, each is based on a `Simo I/o - SW Trig` sub-VI that accommodates the analog stimulus pulse waveform and collects the input CAP data based on a software trigger. Since the events being studied are responses to a stimulus, the stimulus itself is fed back as the trigger input. The software trigger acts as a conditional retrieval in that the incoming signal is not altered, enabling pre-trigger scans to be read, if required [3].

The electroneurology VIs can accept an arbitrary number of inputs; however, there are some calculations that are applied only to a single nerve recording electrode. For example, in the calculation of the fundamental relationships for the nerve as in the strength/duration curve or the restitution curve, the data involved in the measurement are only concerned with a single electrode. When conduction velocities are calculated, however, they are determined for every successive pair of electrodes, since conduction velocity can change as a function of distance along a nerve.

The graphical user interfaces (GUIs) for each of these VIs are intended to be as similar as possible, so as to minimize time spent learning the interface. As data are collected they are typically displayed in strip chart format to the right of the window, whereas output analysis is usually displayed to the left. User inputs are collected in groupings based on function. Some programmers may prefer to hide many of the setup inputs such as scan rate and channels, whereas our VIs are designed to include all this information. In this way, instructors may decide for themselves to what depth they want their students to learn about these parameters and issues associated with them. Initiation of the program compiles the software, reads the proper calibration coefficients, and waits for user input to begin collecting data.

As stated earlier, all of the data acquisition and analysis described in these labs is automated through the included VIs. While that was an important part of the development of these labs, it may not be the proper pedagogical style for everyone. Due to the modular design of the VIs, it should be relatively straightforward to strip away some of the automated analysis and enable students to develop their own routines.

Strength/duration relationship

This experiment is concerned with the threshold relationship for a nerve trunk, i.e. the excitability properties of the nerve. We consider square-pulse current stimuli of variable amplitude (strength) and duration. In fact, several specific combinations of strength and duration can result in the production of a conducted action potential. The strength/duration curve represents a locus of critical points, which are values of strength and duration that result in the generation of an action potential. This curve separates the passive, sub-threshold, non-conducting state from the active conducting state.

A steady potential difference has been demonstrated to exist between the inside and outside of a wide variety of individual excitable cells, such as neurons, cardiac, skeletal, and smooth muscle cells. This transmembrane potential difference is called the resting potential (e.g. −70 mV, inside negative relative to outside of cell) and is the result of an ionic imbalance in sodium (Na^+), calcium (Ca^{2+}), potassium (K^+), and other ions that is maintained in steady-state between the intracellular and extracellular fluid media. The cell is said to be polarized when in the resting state. External stimuli applied to the membrane can alter this resting potential in the form of depolarization (i.e. potential becomes less negative than resting state) or hyperpolarization (i.e. potential becomes more negative). The term repolarization describes the return of the membrane potential from a stimulated state to its original resting state.

The nerve fiber membrane contains voltage and time-dependent ion channels (ion-specific passageways through the membrane), notably Na^+ and K^+ channels. When a region of membrane is partially depolarized so that voltage-gated sodium channels open, Na^+ ions enter and rapidly depolarize the membrane fully. This change in potential causes voltage-dependent ion channels to open allowing ions to flow across the membrane into the intracellular medium of the cell. This effect is short-lived, however, since (a) the change in membrane permeability to Na^+ is brief and transient, and (b) there is a delayed increase in membrane permeability to K^+. Both of these latter effects bring about the repolarization of the membrane to its resting state. The peak change in membrane potential is of the order of 100 mV and the duration of the response (the action potential) depends upon the particular cell type. For nerves, it is of the order of 1 ms.

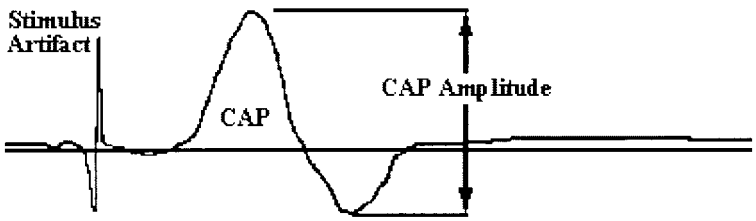

Fig. 2. Typical nerve axon compound action potential (CAP) with stimulus artifact.

The summation of activity from the many component nerve fibers of a nerve trunk gives rise to a triphasic potential waveform known as the compound action potential (CAP). A typical CAP is shown in Fig. 2. The extent to which the membrane must be depolarized in order to trigger an action potential is called its excitability threshold, and this threshold is inversely proportional to the diameter of the nerve fiber. Thus, larger diameter nerve fibers are stimulated more easily than smaller fibers. An action potential is conducted along an axon when a stimulated active region sources current to an adjacent segment of membrane, thus depolarizing it. With depolarization of adequate strength, that region exceeds the voltage threshold for excitability and becomes active. It, in turn, sources current to an adjacent segment, etc.

The stimulus itself contributes a field effect at a distance to the recording amplifier, resulting in a stimulus artifact. This artifact occurs simultaneously with the time of the stimulus delivery, whereas the conducted nerve impulse follows with a delay. One can verify that the conducted waveform is not a second stimulus artifact by reversing the polarity of the stimulus. The artifact changes polarity, whereas the CAP waveform does not. Stimulus artifact is a persistent problem in recording CAPs from nerves. This is particularly true when the stimulus duration is long. As a practical matter, the problem can be observed by first evoking a CAP at a specified stimulus amplitude and duration (e.g. 2 V and 0.05 ms, respectively), and then gradually increasing the duration (with constant amplitude) to about 1 ms. Eventually the stimulus artifact 'walks up' the rising portion of the CAP, interfering with the waveform. To minimize artifact, stimulating and recording compartments should be formed and separated to the greatest extent possible. Often placing a ground electrode between the compartments is helpful in minimizing artifact. In selecting stimuli, it is better to select a brief intense stimulus, rather than a long weak pulse.

Since the sciatic nerve constitutes a bundle of nerve fibers of different diameters, the threshold properties of a nerve trunk will differ from those of an individual neuron. Larger fibers are excited at the lowest stimulus strengths, and smaller fibers at higher strengths. This gives rise to the concept of a 'threshold zone' rather than a single threshold value as for the single fiber. The lower end of the threshold zone denotes the stimulus strength where the CAP first appears. The amplitude, duration and overall waveshape change, as stimuli of greater strength are applied (recruitment of active fibers). Finally, a stimulus strength is reached beyond which no further changes are noted in the CAP. This is labeled the maximal stimulus.

The 'threshold zone' identified above detailed a change in CAP response with increasing voltage. Similar alterations in the CAP can be elicited by changing the duration of the stimulus instead of the voltage level, as demonstrated in Fig. 3. Consider an applied voltage of a particular duration that is just sufficient to elicit the maximal CAP for the nerve, i.e. all fibers within the trunk contribute to the response.

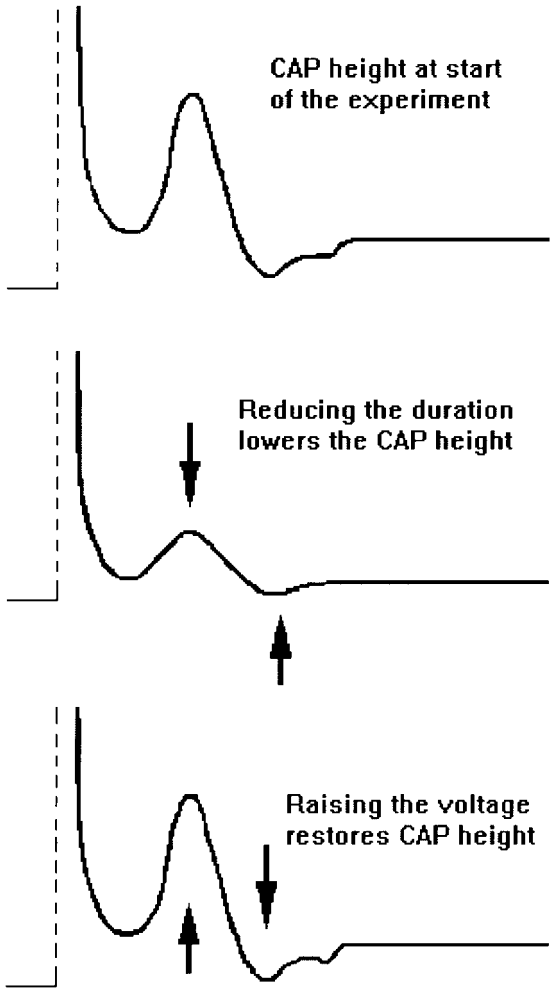

Fig. 3. Demonstration of effects of stimulus strength and duration on resultant nerve compound action potential.

Any stimulus of a higher voltage or duration is called a 'supramaximal' stimulus. Lowering either voltage or duration causes some axons to drop out, thus reducing the overall height of the compound action potential. In forming the strength/duration (S-D) relationship for a nerve trunk, we obtain a family of S-D relationships with graded stimulus intensity from threshold to maximal stimulus strength.

The front panel and block diagram of the `NrvSD` VI that performs this experiment are shown in Figs 4 and 5, respectively. The experiment starts with the longest stimulus duration that results in a clearly defined CAP. The width should be a millisecond or so. Select a stimulus voltage that gives a peak-to-peak action potential amplitude that is about one-half the maximum possible amplitude that was determined from a previous recruitment study. The algorithm then iterates through various strength-duration combinations to provide a single S-D curve that depicts the S-D relationship for a given CAP amplitude. This can be repeated for different CAP amplitudes to develop a family of curves demonstrating the global S-D characteristics of the nerve trunk. A qualifying assumption is that, as stimulus parameters are changed, a restoration to this same amplitude means that the same axons are being stimulated.

The VI automatically determines and records the peak-to-peak amplitude of the CAP for the initial voltage and duration. The stimulus duration is then incrementally decreased by a set amount (typically 0.02–0.05 ms). The waveform height is again determined and compared to the original. If it's smaller, as expected, the voltage level is increased and the test is rerun. This continues until the amplitude is within 3% of the original. At that point, the voltage is recorded and the cycle is repeated at the next duration value. This continues until the duration is less than 30 μs, below which a stimulus of more than the 10 V hardware limit is usually required to generate the expected amplitude. A schematic flow chart is included as Fig. 6 to more clearly delineate the programmatic flow.

It should be noted that the `Apply Cal + t` sub-VI included is a C/C++ subroutine incorporated in a code interface node (CIN) that essentially calibrates and timestamps the recorded data. It will work as is on a Windows 95/98 platform, but must be recompiled on other platforms. However, this sub-VI is not at all necessary to the operation of the experiment. It is used simply to enhance charting and data storage features within these experiments.

More advanced experiments have also been developed. One problem often encountered in electrophysiological studies is the presence of stimulus artifact. Several methods have been developed for estimating the artifact and removing it from the corrupted signal [4]. A stimulus artifact rejection routine is often used in conjunction with the VIs developed for these labs. Care must be taken to use the correct estimated artifact waveform for cancellation, which presumably has been developed using experimental settings that are identical to those used in the experiment.

A second issue commonly encountered is the effect of the volume conductor within which the signals are generated. An experiment utilizing an excised spinal column/sciatic nerve preparation focuses on the field potentials within a homogeneous volume conductor and the means to address the associated forward and inverse problems. The volume conductor has a low pass filtering effect on the CAP recorded at the surface of the nerve. The filtering characteristics of the volume conductor can be determined based on knowledge of the material properties of the volume conductor medium (bulk specific conductivity) and the

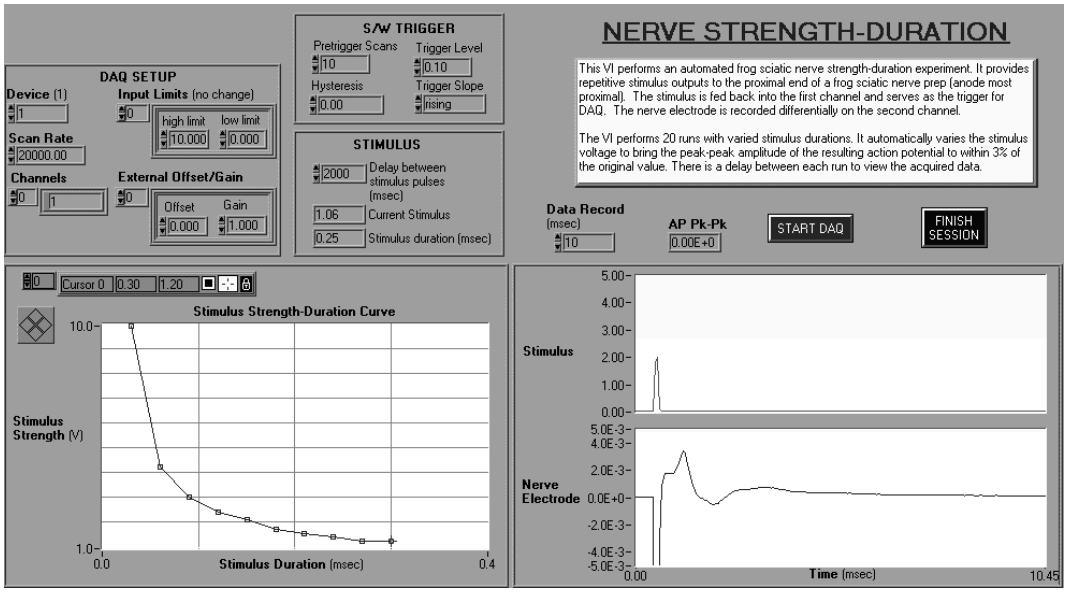

Fig. 4. `NrvSD` VI front panel depicting typical results of a nerve excitation experiment.

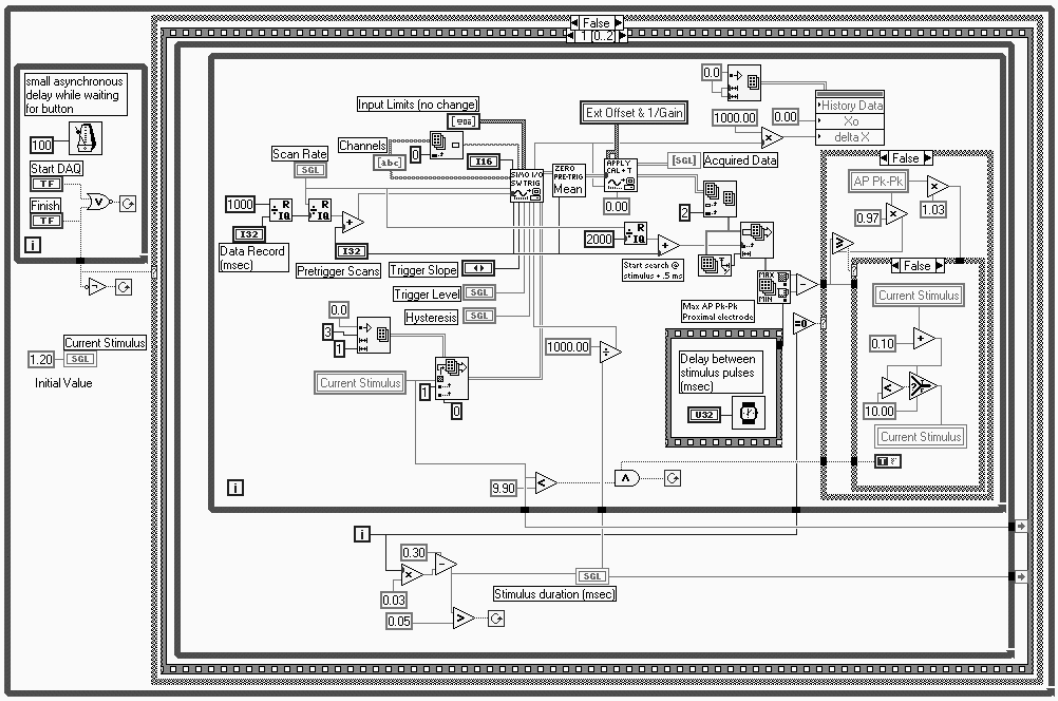

Fig. 5. NrvSD VI block diagram depicting the essential components of the automated nerve excitation algorithm.

geometry of the nerve trunk and surrounding medium [5]. The average CAP conduction velocity is also required, in order to predict the field potential everywhere in the volume conductor.

Cardiac electrophysiology

Cardiac electrophysiology is dedicated to the study of the electrochemical activity of the heart. Studies include electrical activation of individual cells as well as the system-level activation, which results in normal or abnormal heart rhythms. The ECG can serve in diagnosis to provide a variety of information regarding the heart's normal function, as well as predict abnormal function in disease. Similarly, it provides information about heart rhythm abnormalities.

The ECG is the primary focus of investigations in this area. As such, experiments are designed to record ECGs from a variety of animal preparations or from human subjects. Issues such as

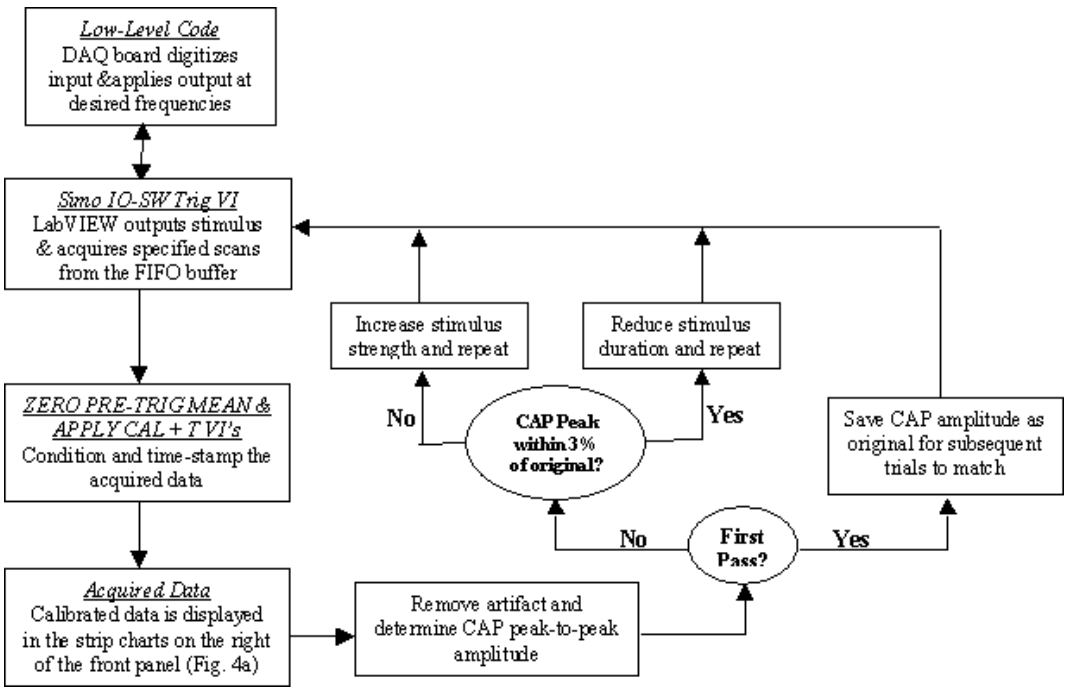

Fig. 6. Flow chart depicting the primary input–output operation of the NrvSD VI algorithm.

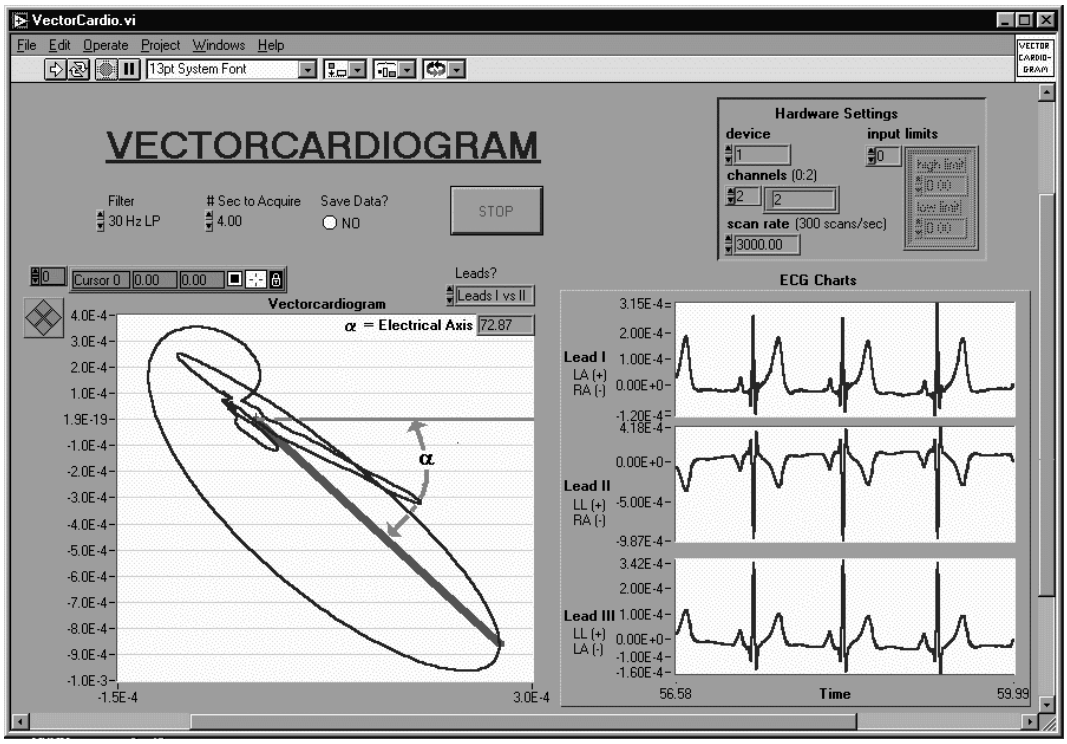

Fig. 7. `VectorCardio` VI front panel depicting typical results of an introductory cardiac electrophysiology lab.

comparing open chest data to surface electrode recordings are encountered as a further extension of the volume conductor problem discussed previously. A second tool introduced in the lab is vectorcardiography, wherein two approximately orthogonal scalar ECG leads that 'look' across the heart horizontally and from top to bottom are plotted on conventional Cartesian axes [6]. The result is a 'loop' in the lead space (horizontal ECG vs. vertical ECG; see Fig. 7), which represents the time-varying electrical activity of the heart. At each instant of time, the net electrical activity of the heart can be represented as an equivalent current dipole source located in the body volume conductor. In the vectorcardiograph (VCG), the electrical center of the cardiac activity is placed at the center of the coordinate system. The current dipole vector extends outward from that center and, with time, its tip traces a locus in the lead space. Since the origin of the dipole vector is fixed at the coordinate center and its orientation is variable, one may visualize the net electrical activity of the heart (see Fig. 7). Normally net dipole vector activity is coincident with the long axis of the loop and it is directed downward and to the right in the plot. The electrical axis of the heart, angle α in Fig. 7, depicts the orientation of the net dipole vector and is a clinically relevant parameter often utilized by physicians to diagnose electrical abnormalities in the heart.

Experiments are established to demonstrate the applicability of the ECG and VCG simultaneously, in real-time (see Fig. 7). These tools are a primary focus in the initial training of students in the field of cardiology. The use of signal processing tools, such as digital filtering, are also introduced in these labs as a demonstration of practical applications of fundamental engineernig concepts.

Advanced experiments are being developed to study the control of heart rate. To achieve changes in heart rate, the right and left vagus nerves (which run from the medulla of the brain stem to the sino-atrial (SA) and atrio-ventricular (AV) nodes of the heart) are electrically via current pulses. These studies enable assessment of the transient phase response characteristics of the pacemaking nodes of the heart, as well as, the steady-state frequency entrainment (capture) characteristics. Relevant data can be obtained from experiments on small laboratory animals such as frog, turtle, rabbit and rat.

Cardiovascular hemodynamics

The electrical excitation of the heart results in a wave of contraction that spreads through the myocardium. The synchronous nature of this contraction results in the efficient pumping of blood through the pulmonic and systemic circulations. Cardiovascular hemodynamics is an area that describes the pumping characteristics of the heart and the associated blood flows and pressures throughout the vasculature. Basic experiments in hemodynamics focus on left ventricular function, blood pressure and flow variations around the cardiovascular loop. In our studies, representative measurements are taken from cannulated arteries and veins, as well as, from catheter-tipped pressure transducers placed within the ventricular chamber(s) of open chest canine and rat heart preparations. Other hemodynamic indices such as stroke

Fig. 8. BioBench front panel depicting data from an open-chest canine experiment.

volume, cardiac output, and ejection fraction can also be calculated.

This area of study is ideal for the turnkey program BioBench, which is written in LabVIEW code. Whereas BioBench currently does not allow sampling rates fast enough for electrophysiology studies, it performs quite well in recording hemodynamic variables. This provides a working, out-of-the-box solution to rapidly moving students into a lab and acquiring data such as that depicted in Fig. 8. Further analysis can then be programmed into LabVIEW, as there are sub-VIs that enable LabVIEW to read the compressed files generated by BioBench.

Advanced experiments in this field introduce modeling efforts with a modified Windkessel model of the closed-loop cardiovascular system. The model-generated pressure waveforms can then be compared with data obtained in the lab. Parameter estimation schemes, such as a multivariable, weighted Levenberg-Marquardt algorithm [7], can then be employed to identify the parameters of the model. Additional experiments incorporate heart rate control via vagal stimulation as well as the effects of sympathetic stimulation on cardiac function (control of myocardial contractility).

DAQ/LabVIEW ISSUES AND CONSIDERATIONS

Although LabVIEW itself is a commercial product, substantial programming is still required to design an optimized system. This is not to simply acquire the data, as there are example DAQ VIs incorporated into LabVIEW and intended for novice users. Rather, VIs that ensure accurate data sampling and appropriately process the data once collected are created using programming knowledge and expertise. That is, a proper understanding of the 'G' programming language and the capabilities of LabVIEW will enhance the efficiency and robustness of the final program. Many features are available in LabVIEW that simplify this task, including Fast Fourier Transform (FFT) and moving average routines as well as peak detection.

It should be noted that LabVIEW, being graphics based, does require significant memory and computer power to operate efficiently. The availability of newer, faster PC's with enhanced capabilities and accessory equipment should ameliorate this problem as time elapses. Another issue to consider is the amount of data to be collected. Collecting large amounts of data will require streaming the data to a hard disk, or other high capacity storage devices such as a Zip/Jaz™ disk drive, whereas lesser amounts of data can be maintained in memory as the program is run. Secondary storage can also create processing inefficiencies. Hence, a judicious choice of storage capacity is necessary to optimize the allocation of resources to the data collection task at hand.

Additionally, it was mentioned earlier that startup and training times for lab personnel and students were minimized with LabVIEW. This is

not to imply that learning LabVIEW to the extent required to design these projects can be accomplished in the beginning of a semester. Rather, using more complex core techniques as sub-VIs enables students to merely modify existing programs to perform their analysis tasks. As students progress through various lab courses, their ability to perform significant scientific research using LabVIEW will be greatly enhanced.

SUMMARY AND CONCLUSIONS

LabVIEW is a powerful tool for students during their education. It also is a tool for use after graduation in the workplace, where students to LabVIEW-based systems, but do not teach them detailed information regarding LabVIEW programming. Primarily, LabVIEW is used as an instructor's aid in development of lab exercises and lab setups. The overall goal of these labs is to provide students with a general background in taking measurements for biomedical engineering applications. The LabVIEW virtual instruments used in the Rice Biomedical Systems and Instrumentation Lab enable students to take measurements without learning a new complex tool, but do not shelter them from fundamental concepts or errors that can occur with the particular measurements.

The lab experiments are designed to interactively teach some of the fundamental theories associated with each field. This not only reinforces basic knowledge, but also trains students in the application of these theories to laboratory research. However, experimental research, by its nature, requires an understanding of the experiment itself, its design and performance, in addition to the objectives of the study. Combining the biological theories with experience in experiment development, live tissue dissection and preparation, and experimental control and data acquisition enhances the quality of education. By establishing and conducting experiments of this nature, the student learns of the complexities inherent in biological, or any other, research.

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