CHAPTER 33

Technological advances in intraoperative neurophysiological monitoring

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33.1. Introduction

Intraoperative neurophysiological monitoring provides a real-time control loop around a system composed of the surgeon, patient, and anesthesiologist. The goals of this control loop are both the reduction of morbidity and a dynamic assessment of the structure–function relationships of the patient's nervous system. This is accomplished by making specific and sensitive measurements that reflect the interactions between the surgeon's operative manipulations and the functioning of the patient's central nervous system (CNS). This requires obtaining real-time measurements of CNS function that can be closely correlated with operative manipulations. To achieve these measurements within a time frame that is of value to the progress of the operation, it is highly advantageous to acquire, process, and display multimodality data both rapidly and simultaneously. In addition, the paucity of trained individuals to interpret this real-time data has led to the development of powerful internet-based remote viewing and communication facilities as a means for overcoming this lack of qualified neurophysiologists.

Many technical advances have led to the ability to acquire multimodality data simultaneously with appropriate acquisition parameters for each data type,

to digitally filter this data with filter settings which are appropriate for each data type, to display the data in flexible displays based on modern graphical user interface technologies, and to support remote internet-based viewing and interpretation of the data as well as continuously available communications between interpreting physician/neurophysiologist and a locally positioned neurotechnologist.

This chapter briefly describes the technical advances which have occurred that allow data to be acquired rapidly from multiple data types simultaneously, including modern stimulation, display, and filtering techniques. Particular attention will be paid to technology which supports remote viewing of data and communication between remote neurophysiologists and local neurotechnologists.

33.2. Multimodality neurophysiological measures

Neurophysiological measures routinely utilized in monitoring can provide a functional map of much of the entire neuroaxis when acquired and viewed either simultaneously or nearly simultaneously. Being able to acquire multimodality data represents an important technical advance; however, being able to do so requires an understanding of the relationships between the physiological generators of the various neurophysiological measures which are utilized and by implication of the requirements which these relationships place on the data acquisition parameters.

For example, during an anterior cord decompression and fusion, it is reasonable to simultaneously acquire bilateral median (MSPs) and posterior tibial nerve evoked potentials (TSPs) as well as

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continuous electromyograms (EMGs); during clipping of a basilar tip aneurysm, it is reasonable to simultaneously monitor auditory brainstem potentials (BAPs), bilateral median nerve somatosensory evoked potentials (MSPs), and digital EEGs; during resection of an acoustic neuroma to simultaneously monitor BAPs, MSPs, continuous EMGs from muscles innervated by various cranial nerves, and evoked EMGs (CN MEPs) from direct stimulation of cranial nerve VII; or during resection of a spinal cord tumor to simultaneously acquired bilateral posterior tibial nerve evoked potentials, transcranially evoked descending activity (TCr MEPs), and continuous EMGs. These are just representative examples of how multimodality data acquisition may be utilized to enhance the efficacy of intraoperative neurophysiological monitoring; but they provide examples which clarify the issues in both neurophysiology and technology. (See Table 1 for definitions of above abbreviations.)

Figure 1 is an example of multimodality data being acquired during the resection of an acoustic neuroma. This figure demonstrates three different data types being simultaneous acquired. These are MSPs, BAPs, and continuous EMGs from three different cranial nerves.

### 33.2.1. Relationships between neurophysiological variables

An understanding of the fundamental similarities and differences of the electrical characteristics of neurophysiological signals, including number of channels, appropriate recording sites, and signal bandwidth to maximize the independent information recorded is necessary. An extensive review of all monitoring modalities is presented in Sclabassi et al. (2006). The recording and stimulating parameters for the EEGs, MSPs, TSPs, BAPs, EMGs, and MEPs are summarized in Table 1.

Table 1

Examples of modalities and modality parameters which may be simultaneously acquired and displayed

Modalities	Stimulation sites	Recording sites	Observation intervals	Stimulus rates	Delay	Bandwidth/ sampling rate
MSPs or	MS and MD	P3/F3, P4/F4 Cv2/Fz, EP	100 ms	3.43 Hz (SM)	100 ms (BS)	1–300/ 2,000 Hz
USPs	US and UD			2.45 Hz (BM)	200 ms (BM)	100–1 kHz/ 4 kHz
TSPs or	TS and TD	Pz/Fz, P3/P4 Cv2/Fz, L1/L2	100 ms	3.43 Hz (SM)	100 ms (BS)	1–300/ 2,000 Hz
PSPs	PS and PD				200 ms (BM)	100–1 kHz/ 4 kHz
BAPs	AS or AD	Cz/A1, Cz/A2 Cz/Cv2	20 ms	17.5 Hz	None	100–1 kHz/ 8 kHz
MEPs	TCr	apmgs	50 ms	Burst	None	3–1 kHz/8 kHz
	CNs	apmgs		5.1 Hz cont.		3–1 kHz/8 kHz
	PedS	apmgs		5.1 Hz cont		3–1 kHz/8 kHz
EEGs	None	10/20 montage	1–4 s	None	None	1–100 Hz/ 500 Hz
EMGs	None	apmgs	50 ms–1 s	None	None	1–1 kHz/8 kHz

Three letter extensions are used for evoked potential (EPs) modalities to allow unique identification of data types (note figures in text). MSP, median nerve EPs; MS, left median nerve; MD, right median nerve; USP, ulnar nerve EPs; US, left ulnar nerve; UD, right ulnar nerve; TSP, posterior tibial nerve EPs; TS, left tibial nerve; TD, right tibial nerve; PSP, common peroneal nerve EPs; PS, left peroneal nerve; PD, right peroneal nerve; BAPs, brainstem auditory evoked potentials; AS, left ear; AD, right ear; no restrictions on stimulation MEPs; TCr, transcranial electrical stimulation; C3/C4 (anode/cathode), right muscle groups; C4/C3 (anode/cathode), left muscle groups; stimulus is 250 Hz burst lasting 20 ms (five pulses); 200 µs width, 150 V; CNs, all cranial nerves—recording from appropriate muscle groups (apmgs), stimulus is 5.1 Hz, continuously; intensity is 0.1–10 V; PedS, pedicle screws recording from appropriate muscle groups (apmgs), stimulus is 5.1 Hz, continuously, intensity is 5–20 V; SM, single modality stimulation; BS, both sides, for example, MS/MD with 100 ms delay between; BM, two modality stimulation; BS, both sides, for example, MS/MD than TS/TD; MEPs—TCr—must be synchronized with MSPs/TSPs.
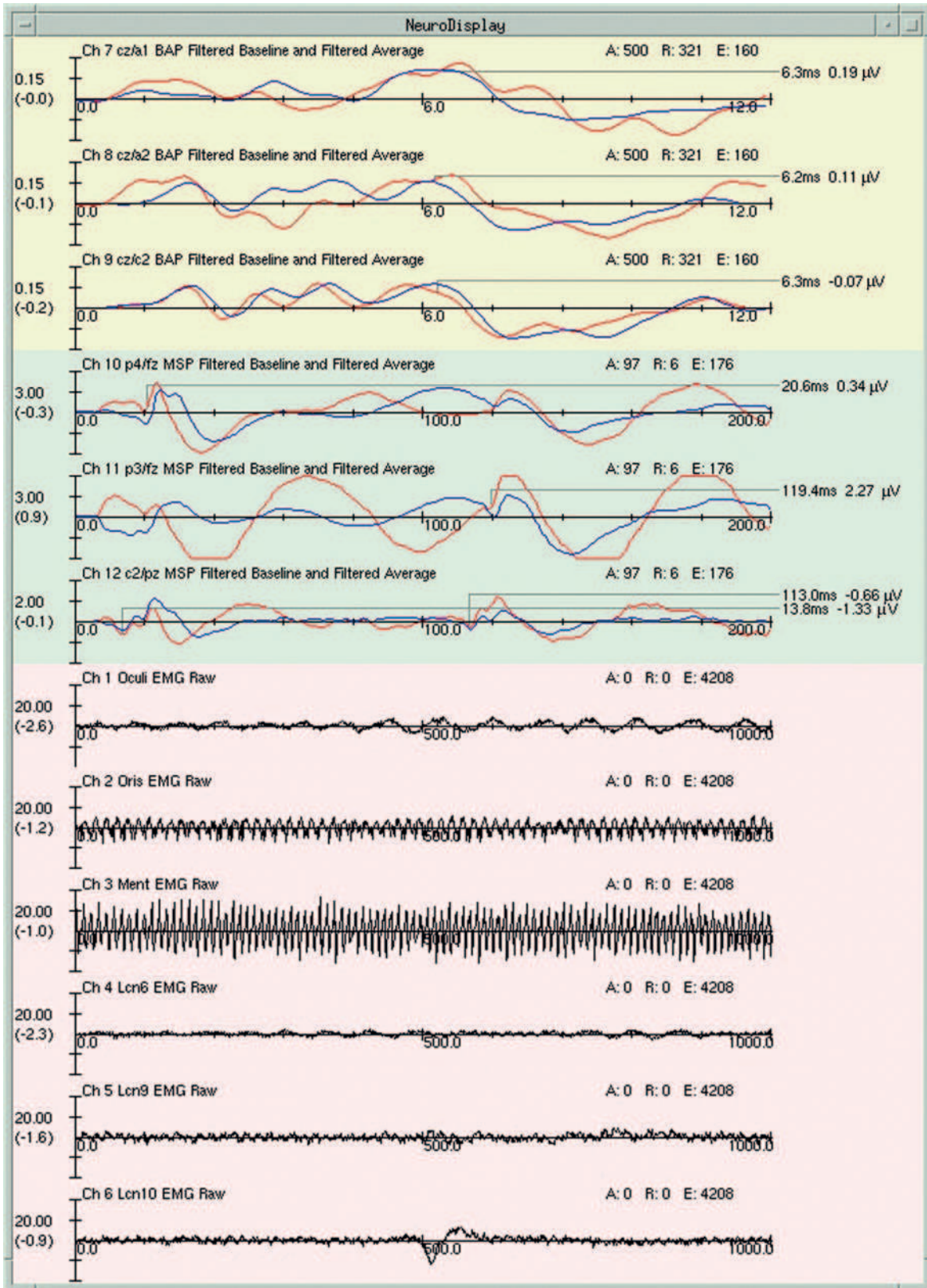
33.3. Technological features supporting data acquisition

Much of the material related to acquiring and displaying data is discussed elsewhere in this volume; thus we shall discuss these issues from the perspective of multimodality acquisition and display. To make this discussion concrete, we shall frame it in the context of the system which we utilize (NeuroNet©; Computational Diagnostics, Inc.) which is a system developed in our group to support multimodality data acquisition and remote professional supervision and which is a distributed computing system based on workstation and network technology, which provides user-transparent, shared file systems and powerful interprocess communication protocols to facilitate sharing and consulting on real-time multidimensional neurophysiological data (Sclabassi et al., 1987, 1996; Krieger et al., 1988, 1991; Simon et al., 1995). Other systems also have these properties, thus this discussion is not intended as an endorsement of this particular system but is purely a convenient didactic approach to the discussion of the technology.

The concept behind this system is that each data acquisition node or viewing node is analogous to a neuron in a network (Fig. 3), and has an important feature in that the communication between these nodes is integral to the functioning of the system. All acquisition software is integrated; that is, there is no concept of separate packages for each type of data being collected. This provides maximum capability for collecting and analyzing combinations of different data types. The EEG capabilities include compressed spectral arrays on all available channels, digital filtering of EEG, and real-time spectral computations on the incoming data with arbitrary length spectral averages. The EMG capabilities include acquiring spontaneous and evoked data (MEPs); while the evoked potential acquisition capabilities include simultaneous mixed modalities with appropriate sampling rates,

observation intervals, digital filtering, and noise estimation. The system provides real-time remote viewing of all acquired data, multiway audio or text communication across the network, and unified user interfaces for local and remote systems, requiring familiarity with only one user interface (Krieger et al., 1988, 1991; Sclabassi et al., 1987, 1996). Some versions of the system have also included real-time video streams for operating microscopes or endoscopes (Sclabassi et al., 1991, Nardi et al., 1993; Simon et al., 1995).

This system permits simultaneous data collection and on-screen viewing of multiple modalities; each with user-determined observation intervals and stimulus rates which can be independently displayed and processed in real time on any other system on the network.

All data manipulations are handled by calls to a common data file library (Neuro Data File or NDF), a file system developed for use in this NeuroNet system. NDF uses a specific convenient support structure (Neuro Data Structure or NDS). NDS supports the concept of a "*case abstraction*," that is a logical grouping of all data pertaining to a single patient. Different data streams are identified and managed by a "*channel manager*" structure. Data types (Table 1) are defined for classes of neurophysiologic, physiologic, and anesthesiologic data. The channel manager contains all pertinent information for each data type in its header portion, and handles variable length records.

This system uses an extensive package for evoked potential data collection and presentation. All modalities may be collected individually or mixed simultaneously. Data trending over time is flexible in that each channel of each modality may be independently displayed and controlled. Examples of processing available for all signals include digital filtering, standard averaging, odd/even averaging, noise estimation, and peak marking (both time and amplitude).

The user may enter comments at any time during data collection and may store and retrieve comments from a

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Fig. 1. Multimodality data acquired during resection of an acoustic neuroma displayed in NeuroDisplay. Twelve channels of data are shown with different sensitivities and observation intervals dependent on the data type. Channels 7, 8, and 9 (top three) are BAP data acquired from left ear stimulation with an observation interval of 12 ms, stimulus rate of 17.4 Hz, and number of stimuli being 512. Channels 10, 11, and 12 (second group of three) are MSPs to MS and MD stimulation 100 ms apart. The observation interval in this case is 200 ms, the stimulus rate is 2.45 Hz, and 128 stimuli are averaged. The light traces in the top six channels are baseline data; while the dark traces are current data. Channels 1 through 6 are continuous cranial nerve EMGs, with Channels 1 through 3 (third group of three) being from the facial nerve and the last three from cranial nerves VI, IX, and X, respectively. Irritation activity is shown on the mentalis branch of CN VII. The observation interval in all six channels is 1,000 ms. Baselines may also be displayed for continuous data if desired. Sensitivities for each channel are noted on the left side of the display.

list of predefined comments for quick annotation of a currently collected record through a pop-up window. These comments are automatically appended to the data record and appear remotely in (Figs. 5 and 6) windows. Baseline data may be displayed for any waveform (both in the real-time displays and in trended displays). The baselines may be retrieved from any channel of any data file, thereby permitting the inclusion of baselines from preoperative studies. Artifact rejection is also fully user controlled. The user may define two time windows per channel for artifact rejection. Furthermore, the amplitude rejection criterion is user-settable along with a "spike allowance" parameter which permits a percentage of the data to exceed the artifact rejection limits without throwing away the trial. The data acquisition nodes provide the additional flexibility of being able to operate independently of the network. Whether networked or standing alone, the acquisition nodes provide complete user-control over every acquisition parameter.

33.3.1. Technical considerations

The acquisition of multimodality data imposes great flexibility requirements on the electronics of the system. Since multiple input data channels can be reformatted to construct multiple data display channels (traces), all input data channels are required to have the same input impedance, anti-aliasing analog filter characteristics, signal gain, and sampling frequency. All specific sampling, filtering, and sensitivity adjustment are performed digitally when the data are reformatted for the desired signal channels.

33.3.1.1. Signal acquisition
Signal acquisition from the perspective that multimodality data places on a system is slightly different than when systems are conceived of as acquiring single modality data. These differences in approach come from the required flexibility of combining data acquired from different electrodes in multiple combinations to be consistent with different data types. For example, P3/F3 could be both utilized for recording MSPs to right median nerve stimulation and an EEG channel at the same time.

Also P3/P4 could be utilized at the same time as a component of the montage for recording TSPs.

33.3.1.2. Analog filtering
Unwanted activity (noise) originates from both the signal recorded from the subject and electrical devices in the immediate neighborhood of the recording equipment. Since the aim of evoked potential recording is to ensure a large, clear response with the least possible noise contamination (i.e., the best signal-to-noise ratio possible), the elimination of these unwanted signal components is essential. This elimination is accomplished partially through the use of analog filtering techniques combined with averaging and digital filtering. A source of potential noise is the relationship between the sampling frequency and the frequency contents of the neurophysiologic signals. The analog input filters must bandlimit the neurophysiologic signals to less than half the sampling frequency otherwise signal distortions are created by the aliasing of high frequency components into the low frequency spectrum of the signal.

The frequency response characteristics are defined by the high-pass cutoff point (i.e., the frequency above which the amplifier passes the frequency components of the signal essentially unattenuated), the low-pass cutoff point (i.e., the frequency below which the amplifier passes the frequency components of the signal essentially unattenuated), and the rate of attenuation occurring below and above these cutoff points, respectively. Care must be given to providing minimum phase shift through this filtering process as the phase shifts for different frequencies will also introduce signal distortion. Analog filters are provided at preset values in all preamplifiers to act as anti-aliasing filters. In many systems, analog filters are also provided with selectable values at the amplifier stage, even though this feature is probably not useful in the context of multimodality testing where digital filtering is more useful. Care must be taken to ensure that the analog filtering built into the preamplifiers (or in the first stage of the amplification) is not so tight as to provide apparent noise-free data at the expense of significant signal distortion.

33.3.1.3. Signal amplification
Neurophysiologic signals are most commonly amplified using differential amplifiers, that is, amplifiers in which two input channels to the amplifier are differenced. Differencing has the effect of eliminating identical (in-phase) signal components which might be present at each recording electrode (presumably noise), and retaining the signals which are different (out-of-phase) and presumably produced by different physiological generators appropriate for each data type. Important functional specifications for these amplifiers are the input impedance, common mode rejection ratio, sensitivity, gain, noise figure, frequency

response, and output impedance. The input and output impedances determine, respectively, the effectiveness with which an amplifier picks up electrical activity from the electrodes at the scalp and passes it on to other components. The input impedance of the amplifier must be great compared to the impedance between the recording electrodes feeding the amplifier (greater than 100 times larger). The input impedances of modern commercial amplifiers are usually greater than 100 MΩ, and the greater this impedance is the more fidelity is captured in the recorded differential signal. The gain specifies the factor by which an amplifier multiplies the voltage at the input to produce the output voltage. Amplifiers typically have had adjustable gains, with ranges between 1,000 and 500,000; however, with the desire to have all signals as common as possible in characteristics prior to reformatting, a single fixed gain may be used on all amplifiers The availability of 16–18-bit A/D converters allows all neurophysiologically interesting signals to be acquired with the gain being on the order of 80 dB.

33.3.1.4. Common mode rejection ratio

Common mode rejection ratio (CMRR) governs the amplifier efficiency in discriminating between the local potentials of interest and other, usually larger, interference potentials, picked up at both input electrodes (e.g., 60 Hz). Apart from brain activity, bioelectric activity originating from muscles in the head and neck, from the eye and heart are present and as previously mentioned, are likely to be much greater than the evoked potentials of interest. Also present at the scalp will be relatively large induced voltages of extraneous origin arising from other electrical equipment. Amplifiers increase all signals presented across the input leads irrespective of their source by a factor of their gain. With differential amplification, electrical activity from one pair of electrodes connected to the amplifier is compared directly to the activity presented at the other electrode, thus only potential differences between the two input electrodes are amplified. Any potentials which are picked up equally at both electrodes (common mode or in-phase signals) are canceled out and only the voltages developed between the two electrodes (out-of-phase signals) are separated and preferentially amplified. The effectiveness with which a differential amplifier rejects in-phase signals compared to its ability to amplify out-of-phase signals is called the CMRR. Differential amplifiers used in neurophysiologic

investigations typically have CMRRs of greater that 80 dB; that is, an in-phase signal has to be 10,000 times greater than an out-of-phase signal in order for both to be recorded as the same size signal. For efficient rejection of in-phase signals, it is extremely important that the electrode impedances of a pair of electrodes should not only be as low as possible, but as similar as possible for both electrodes of the input pair; since any impedance inequalities will produce amplitude differences in the in-phase activity that will be amplified along with the desired signal. Thus, the observed signal would consist of the desired signal and the component of the in-phase signal due to the impedance imbalance.

33.3.1.5. Sensitivity

The sensitivity of an amplifier specifies the range of input voltages which it will amplify without distortion; that is, it refers to the actual voltage relationship between the amplifier input and output. The amplifiers working range is specified by the minimum input voltage which will produce a specified output voltage suitable for interfacing with other equipment, and the largest output voltage producing an undistorted output voltage. The noise figure for the amplifiers specifies the magnitude of noise inherent in the amplifier itself, independent of all other factors.

33.3.1.6. Analog-to-digital conversion

In order to process data digitally, the analog signals must be sampled using an analog-to-digital (A/D) converter, which has a maximum peak-to-peak input voltage range (e.g., 10 V) and which must be sized with respect to the characteristics of the amplifiers to provide maximum sensitivity. The sampling rate is determined by the frequency content of the signal being measured and the Nyquist sampling criteria, which specifies that the sampling rate must be at least two times greater than the maximum frequency content of the signal. The sampling of a signal at greater than the Nyquist rate avoids signal distortion produced by aliasing due to sampling the signal at too low a sampling rate as mentioned in the discussion on anti-aliasing filters. It is best, in the multimodality situation to sample at higher sampling rates (four to six times the Nyquist rate) and then decimate the data to the desired sampling rate for each combined data channel while the high frequency sampled data is stored for possible recombination to produce other display traces.

Modern A/D converters have a 16–18-bit accuracy, sample and hold circuits for accurate conversion, and

single-channel throughput rates of 40 kHz. The details of these data acquisition elements are not always important to the user; however, it is worthwhile to have some idea that they exist and what their limitations are when attempting to acquire and interpret data at the extremes; for example, auditory brainstem responses which tend to be comparatively small in amplitude and rapidly occurring.

33.3.1.7. Digital filtering

Digital filters enhance the extraction of the signal from the noise. Digital filters have several significant advantages including the ability to introduce zero or constant phase shift (important in assessing latencies in different components), and flexibility in implementation (multiple filtering routines can be utilized dependent on the nature of the data). These calculations are implemented either as convolutions (Krieger et al., 1991), regressions (Krieger and Sclabassi, 1994), or as manipulations on Fourier transforms (Sclabassi and Harper, 1973).

33.3.1.8. Stimulus timing

Multimodality data requires integrated timing capabilities for multiple data types. Most systems will include multiple programmable real-time clocks used to time interstimulus intervals, and delays between the various stimulus channels, which normally have a time resolution of at least 10 μs. For most flexible use, multimodality systems require a separate timing clock for each independent triggered data type.

33.3.1.9. Multimodality signal averaging

Evoked potentials are typically a fraction of the size of the spontaneous brain activity appearing in the background EEG, and about one thousandth the size of the other physiological and extraneous potentials with which they are intermixed. The most effective method for extracting the signal of interest from the noise, after amplifying the signal with differential amplifiers, is to use signal averaging, which is in effect a cross-correlation between a point-process defined by the occurrence of the stimuli and the recorded evoked activity (i.e., an optimal filter). In averaging, the signal component at each point is coherent and adds directly, while the background and noise components tend to be statistically independent and summate in a more-or-less RMS fashion.

The usefulness of averaging as a signal extraction technique is dependent on the assumption that the observed data is stationary, that is, the data is not changing rapidly. This assumption reenforces the need to acquire data as rapidly as possible for any single average. We have been investigating techniques for estimating time-varying evoked potentials (Krieger and Sclabassi, 1994). In addition to the classical averaging techniques, a number of modified averaging techniques have been developed and found to be useful. These include odd/even averaging (where two responses are computed for each data channel, one from the even number stimuli, the other from the odd numbered stimuli), moving averaging (which allows a sliding average to be computed), averaging to bursting trains (which allows high frequency response properties to be studied and which are also useful in producing TCr MEPs at low stimulus intensities), random train stimulation (which allows nonlinear properties and system interactions to be characterized) (Sclabassi et al., 1977), and noise estimation by plus/minus averaging (which allows the residual noise on a response to be estimated and is extremely useful when a patient has significant pathology).

33.3.2. User interfaces

All user interfaces in our NeuroNet system are based on X-windows and Motif and allow for the manipulation and presentation of all data types. The baseline responses are displayed as a background display on the computer monitor so that differences may be automatically calculated and displayed. A waterfall display window (NeuroView) is used to follow the patterns of the change over a period of time during the case with cascaded data. New responses are automatically updated to this display, whether locally or remotely, as they are saved from the current data display (NeuroDisplay). Thus, the waterfall display provides a comparative record of the patient's data and facilitates the process of identifying significant changes in activity either locally or remotely.

33.3.2.1. Data display

This again is discussed specifically for the system we use as a didactic convenience and example. Other systems are available with their own approaches to address such issues. NeuroDisplay is an oscilloscope style display, which allows current physiological data to be reviewed on the local data acquisition machine (see Fig. 1). It uses an X-Windows-based program, and all the graphics programming has been coded using Xt Intrinsics, XLib, and Motif convenience

functions. NeuroDisplay consists of a display area, for display waveforms, and a menu. The options available from the menu allow the user to control how the display area presents data. NeuroDisplay is a user interface screen and constitutes the front-end to NeuroNet.

NeuroView is used to view data being acquired either locally (Fig. 2) or across the network (Fig. 5). NeuroView is also an X-Windows-based program, and all the graphics programming has been coded using Xt Intrinsics, XLib, and Motif convenience functions. NeuroView relies on NNCP to support network transport, and NDF to support data access. NeuroView has five distinct components: the Application Shell, the Spawner, the Help File Reader, the Application Thread, and the Display Shell. All of these components, except the Help File Reader, rely on a context structure modeled after a process context, which contains all the information needed to characterize the state of a display shell. The Application Shell consists of the user interface, callback functions to set elements of the context structure, the interface to the Spawner, and the interface to the Help File Reader.

Neurophysiologic data is captured in an observation window and displayed in a window of the same length of time. However, many measures produced by the same stimulus occur at different latencies with respect to that stimulus. Thus, useful methods of data display included in the software are being able to tailor the observation window to the expected latency of the interesting component of the response. For example, short-latency potentials typically occur within 20 ms of the stimulus; while intermediate latency potentials occur within the first 100 ms of the stimulus presentation. Thus, the optimal observation of these different components is facilitated by the capability to specify different observation windows for different waves of interest, being observed at different regions of time after the stimulus presentation. In addition, simple and easy display facilities are provided for presenting digitally filtered data, spectra, and noise estimates along with the primary data, as are capabilities for identifying, tracking, and comparing current data against baseline data.

33.3.3. Remote monitoring system

The NeuroNet Remote Monitoring System (NNRMS) is used by neurophysiologists to remotely monitoring surgical cases in near real time. It interacts with the Neuro processes previously described to automatically create remote monitoring display windows (NeuroView windows in Figs. 5 and 6) for each modality of each case. This system can also be used to review archived data, or monitor an ongoing case by manual selection. Also lists of comments annotated to the data records are automatically produced (Fig. 6C) to facilitate the remote viewer understanding the case context.

33.3.3.1. Network structure

A fundamental and unique feature of the NeuroNet system is its ability to support multiple mobile instrumentation carts and remote-viewer computers (Fig. 3). All data acquired at any one of the instrumentation carts may be viewed at any other cart or computer (configured to be a node) connected to the network. Thus, one neurophysiologist can monitor several procedures at the same time. The system has remote monitoring built-in to provide shared data as well as instant typed (Fig. 4) or audio communications between users. In addition, when on the network, NeuroNet can automatically provide data backup as the data is collected by the instrument carts. The facilities are designed to work across any intranet/internet architecture. Therefore, virtually any site can be connected in some form to another site. Data can be displayed and analyzed anywhere within the configured network and performance is even supported through low bandwidth modem connectivity.

33.3.3.2. NeuroNet Communication Protocol (NNCP)

The NeuroNet Communication Protocol level encapsulates the communication control structure. This level provides global naming and location information. Remote data access is provided by a robust software system organized in two layers which are supported by distributed daemons: a Parallel Virtual Machine (PVM) Daemon (pvmd3); and an Information Services Daemon (ISD). PVM enables a collection of heterogeneous computers to be used as a coherent and flexible concurrent computational resource (Geist et al., 1997). PVM provides global naming services, dynamic process groups, message passing, multicasting, and global synchronization functions. A PVM daemon (pvmd3) runs on each NeuroNet machine. In addition, there is a single instance of the PVM group server daemon on the network.

In the NNRMS context, the Display Shell and the File reader are processes in the virtual machine that

exchange NeuroNet data. A typical NNRMS configuration is illustrated in Fig. 3. A collection of computers accessible to each other through a TCP/IP network connection are folded into a PVM virtual machine by a master PVM node which is running the Spawner process. These nodes may be located in different hospitals (or anywhere in the world, for that matter, as long as they are accessible through the internet).

An ISD runs on each NeuroNet machine. This deamon service requests lists of active cases. It utilizes the message transport services provided by PVM to receive requests and service. Thus, the ISD is the server process in a client server architecture, where the applications are the clients. Each ISD maintains a list of both historical and active cases on the machine where it is running. Active cases are defined as those

which have collected and saved data within the past hour.

Multiple applications may be run on each node. The applications use case listings and case data, fetched by the ISDs and transported by the pvmd3s, to generate data displays. They utilize the dynamic group services provided by PVM to identify server processes (ISDs) and the PVM message transport services to send requests and receive responses.

Three main components constitute NNRMS: the Spawner, the Display Shell, and the File Reader. The Spawner is responsible for monitoring the network of computer node configures in the NeuroNet system. Towards this end, the NNRMS maintains a complete list of computer nodes which can register with a *location broker Daemon.* On each network
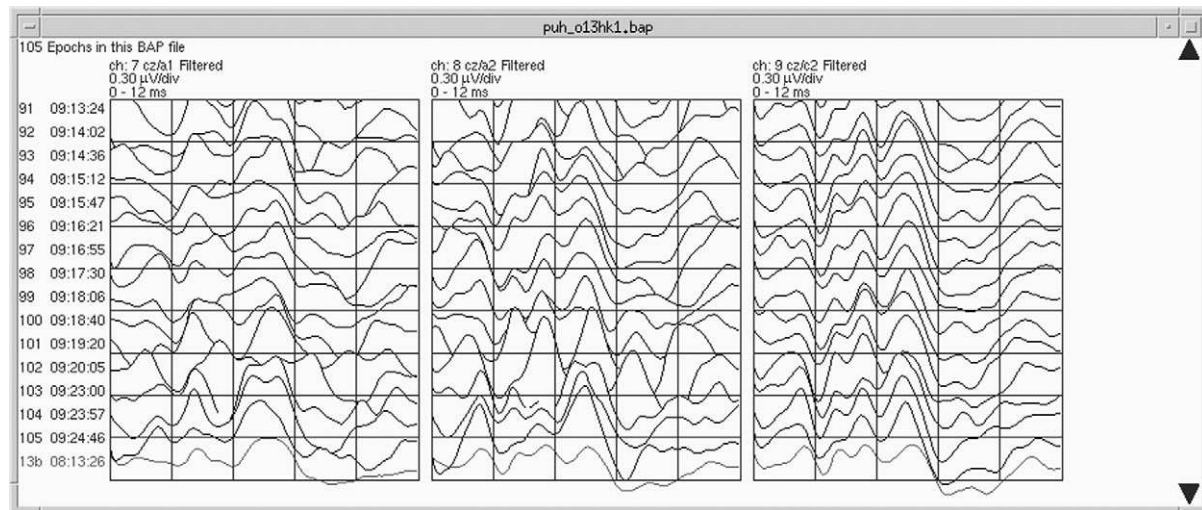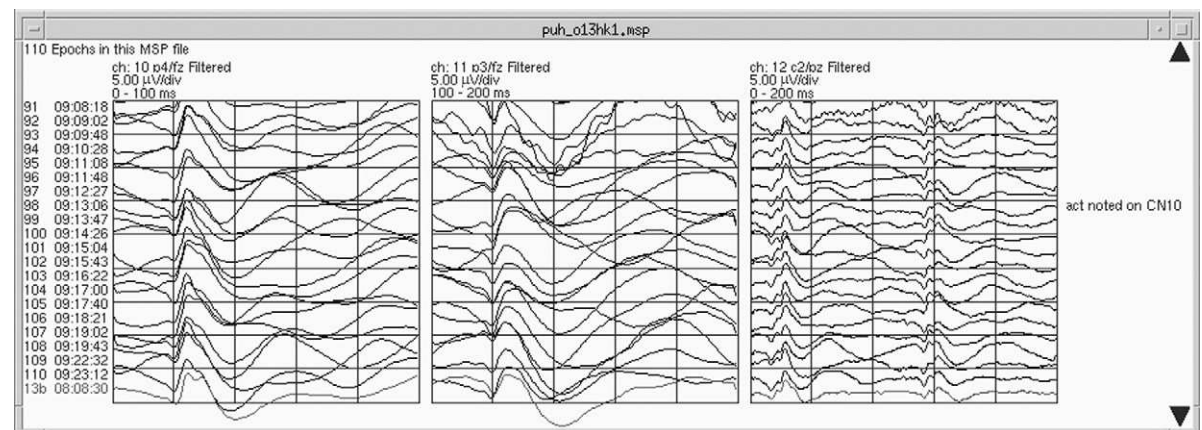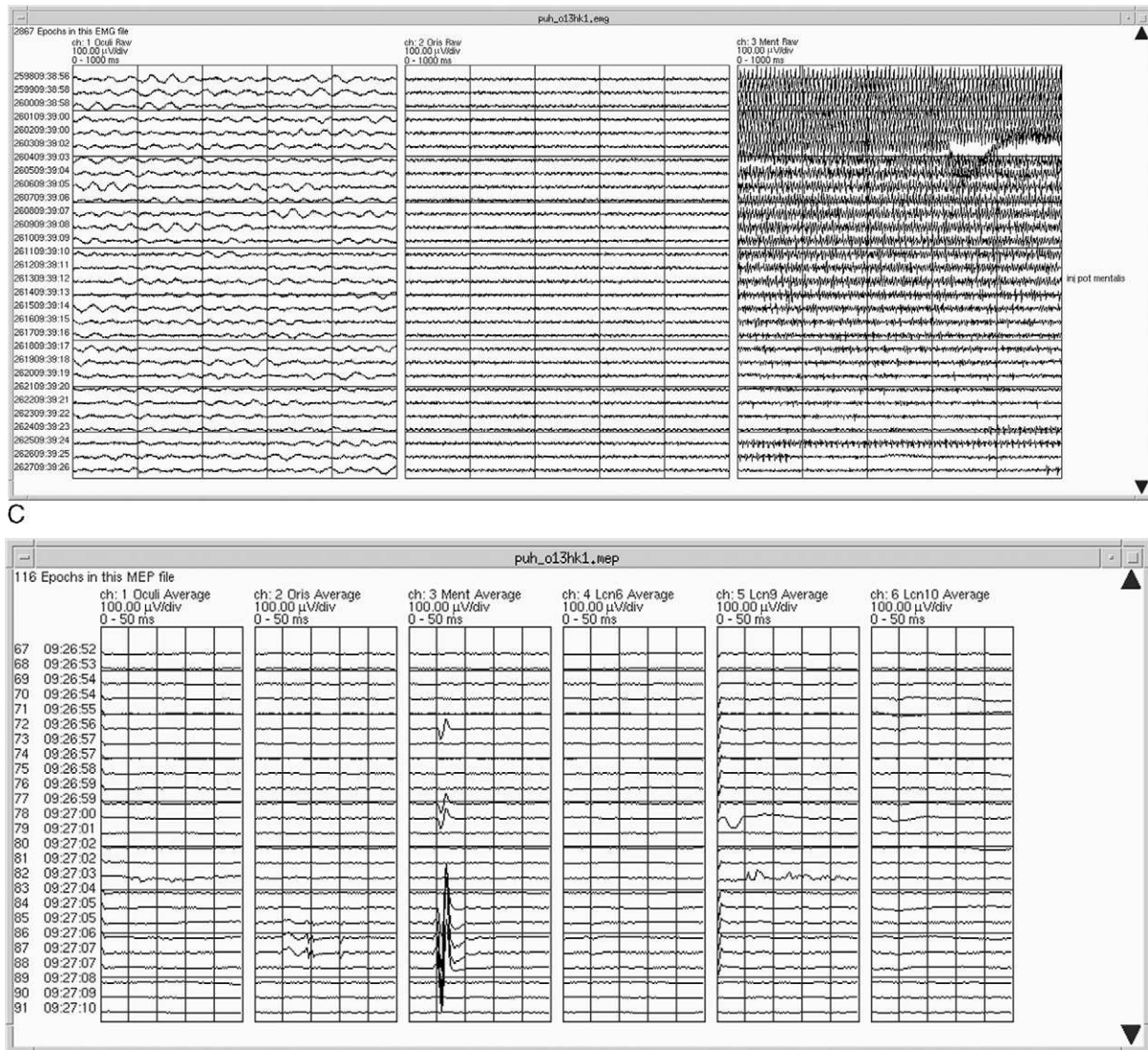

(Fig. 2 continued)

Fig. 2. Local waterfall displays (NeuroView) of data from case in Fig. 1 providing cascaded history of the case for local viewing. Neurotechnologists have complete control over size of the windows, positions on the computer monitor, number of channels for each modality displayed, numbers of traces displayed, colors of traces and background, observation interval, sensitivity, numbers of traces, and digital filtering of data. These may be set the same as in the Neurodisplay window (automatically) or may send them to the preferences of the neurotechnologists in the operating room. A: presents BAP data from this case as displayed in a cascade display. The light trace at the bottom of the figure is baseline data, which may be different from that used in NeuroDisplay (Fig. 1). Fifteen traces are stacked and the observation filter is as in Fig. 1. This data is also being digitally filtered. B: presents the MSP data being collected. In this figure, the observation interval for the data is different with each frame having an observation interval of 100 ms. Baseline date for the MS responses (frame 1) and the MD responses (frame 2) is again the light trace at the bottom of the figure. Frame 3 presents the subcortical data for both MS and MD stimulation. The attached note notes irritation activity occurring on CN X. C: presents the continuous EMG traces also being acquired simultaneously again with a 1,000 ms observation interval. In this figure, only the traces from the three branches of CN VII are shown. Frame 3 demonstrates irritation activity being noted from the mentalis branch of CN VII. Also noted the attached note noting irritation EMG activity on the mentalis branch. D: presents data not shown in Fig. 1; namely evoked EMGs (MEPs) obtained over simultaneously by electrical stimulation through the tumor. In this figure, all six EMG channels from which continuous EMGs are also being recorded are shown. However, the observation interval is now 50 ms, synchronized to the occurrence of the stimulus pulse. The stimulus rate used in this situation was 5.3 Hz. Note the MEP in frame evoked by stimulation of the mentalis branch of CN VII.
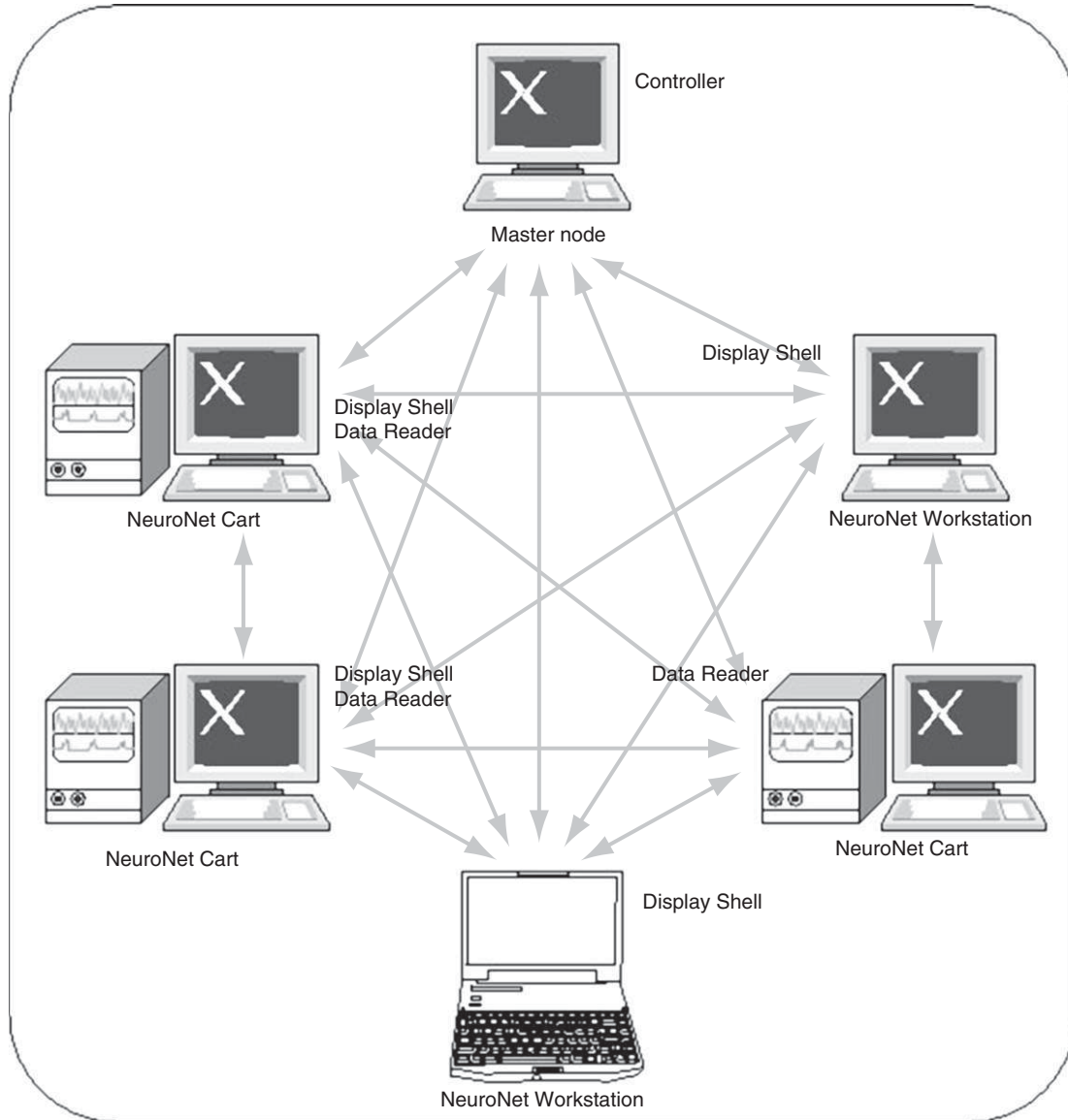
Fig. 3. NeuroNet Remote Monitoring System (NNRMS). The Master node executes a Spawner process based on lists of system allowed into the network. This Spawner process activates all communication processes between nodes when they are attached to the internet. The figure shows three NeuroNet data acquisition carts entered into the network, an instance of the File Reader process is executing on each of these nodes. Two nodes in this example are workstations (installed in the neurophysiologist's office) and they execute only an instance of the Display Shell. The NeuroNet carts can also run a Display Shell so that they can also function as viewing nodes for other cases as well as for the data being collected locally. Thus, many data acquisition systems have multiple display screens which allow neurophysiologists to be in one operating room and be interacting with cases in other rooms.

monitoring pass, the Spawner compares its list of nodes with the list of nodes registered with the location broker. Then, it attempts to connect to the unregistered nodes to fold them into the NNRMS.

The connection between the Spawner and an unregistered node is made through Secure SHell public/private authentication. The Spawner is an entry point where the ISD can notify NeuroView that a remote process is active. The Spawner is also responsible for starting Display shells on user requests. The Application Thread is a routine responsible for waiting for data from an acquisition process or a file and updating the
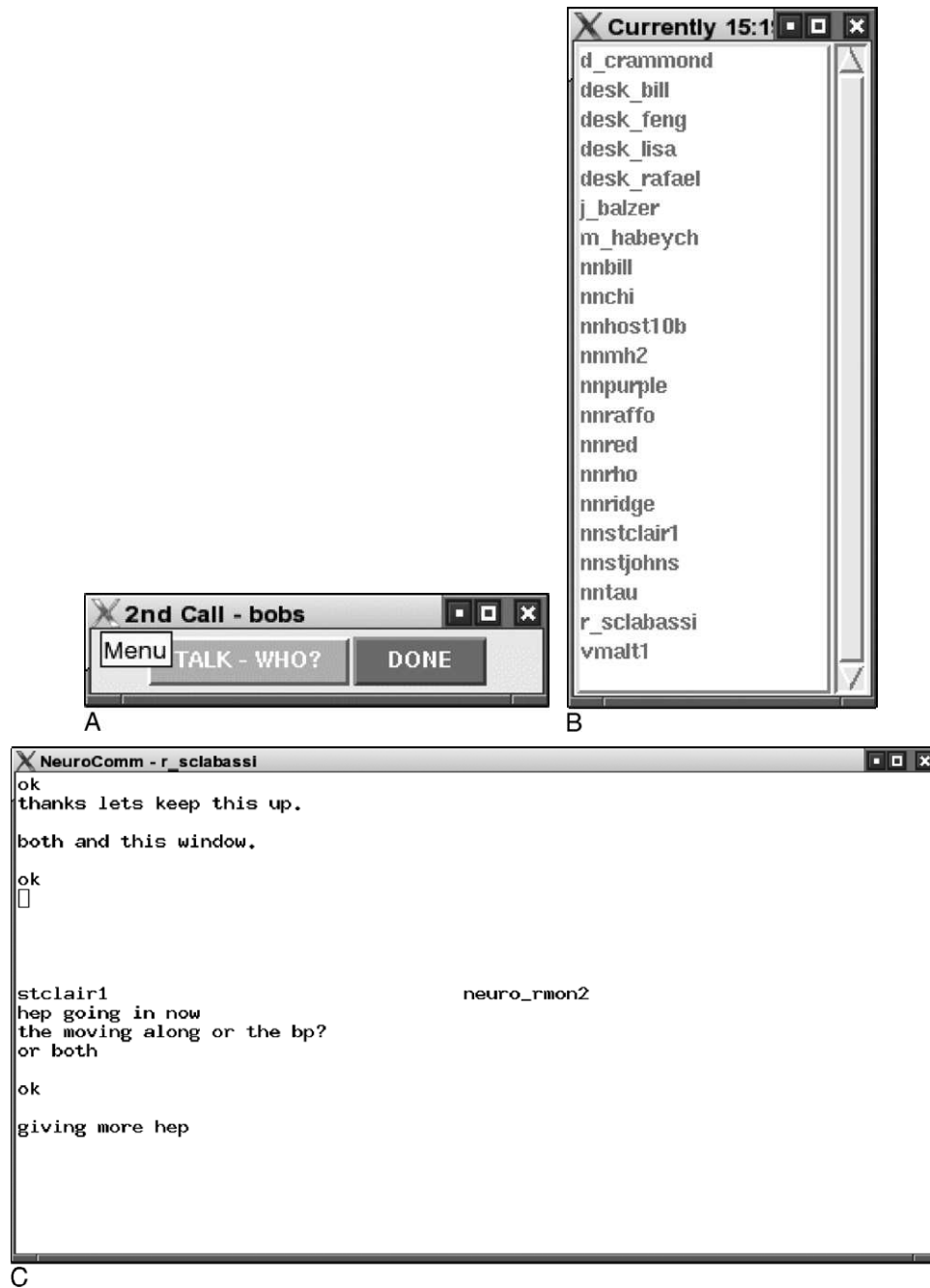
Fig. 4. Example of communication facilities provided within the NeuroNet system. A: is a communication control window which is constructed to provide a limited set of nodes which an individual can communicate with. In our practice, we segregate the systems by place in a call rotation. All communication facilities may be started by all neurophysiologists and all neurotechnologists. B: presents a list of nodes entered into the list for second call at that particular time. This list will expand or contract depending on what systems are on the network at any given time. The authors of this chapter, who are all neurophysiologists in our group, are all available on-line, as are a number of support personnel. In this list, only one data acquisition node (nnstclair1) is actually listed. C: presents the real-time communication going on between one of our neurophysiologists and a neurotechnologist using that particular data acquisition node during a carotid endarterectomy. The top half of the screen are the comments from the neurophysiologists. The bottom half are the comments from the neurotechnologists, and the line in the middle identifies the NeuroNet data acquisition cart (stclair1) and the call rotation (neuro_rmon2).

associated Display shell as necessary. The Help Reader allows the user to obtain online Help about NeuroView. It consists of an index of topics and a scrollable area for displaying the help file.

The Display Shell is the component of the NNRMS that the user interacts with most frequently. The shell is composed of a drawing area, widgets the user utilizes to select a style of information display, and all the functions actually required to perform the display. The shell is responsible for managing the monitoring display

windows. As each case comes online, the Display Shell creates a new window in which the neurophysiological data being acquired is displayed. The Display Shell contacts the File Reader on the node with the new case and requests the data as it is acquired. Examples of remote NeuroView windows are shown in Fig. 5 for the case in Figs. 1 and 2, and Fig. 6 for the communication facilities presented in Fig. 4.

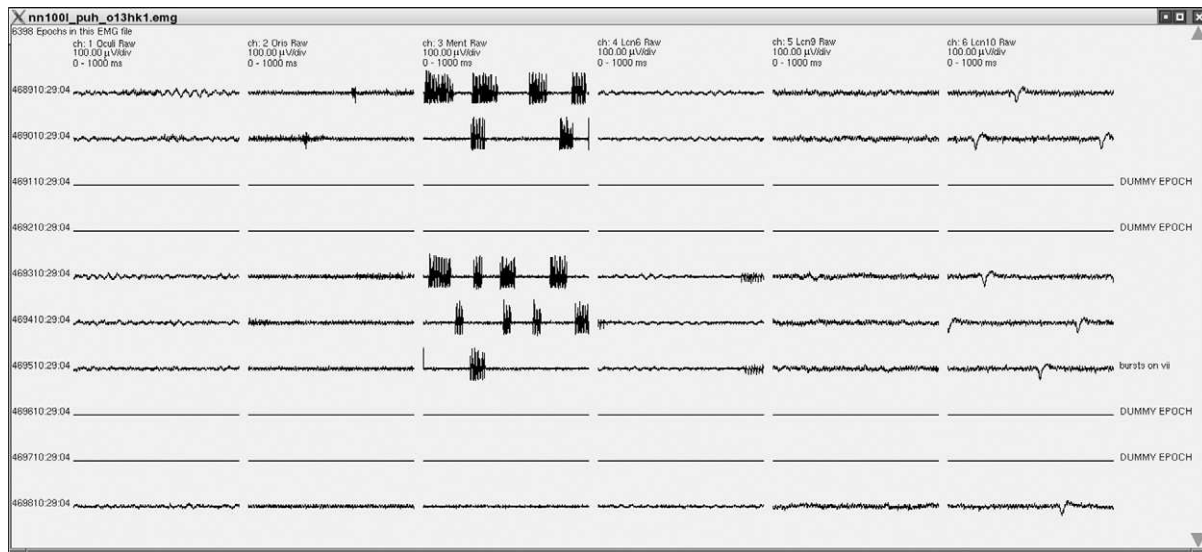For each monitoring window, a case "*context*" is created. The context data structure contains all the
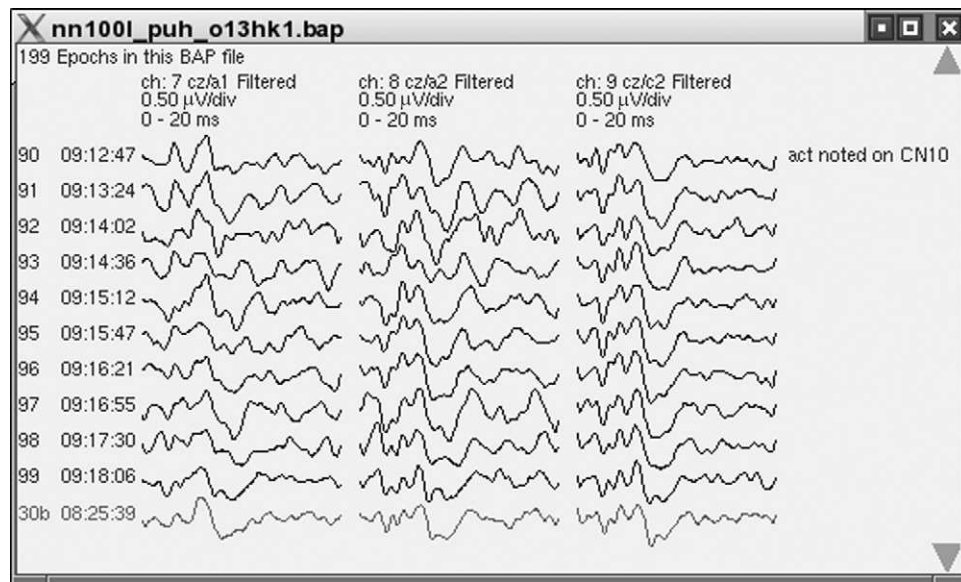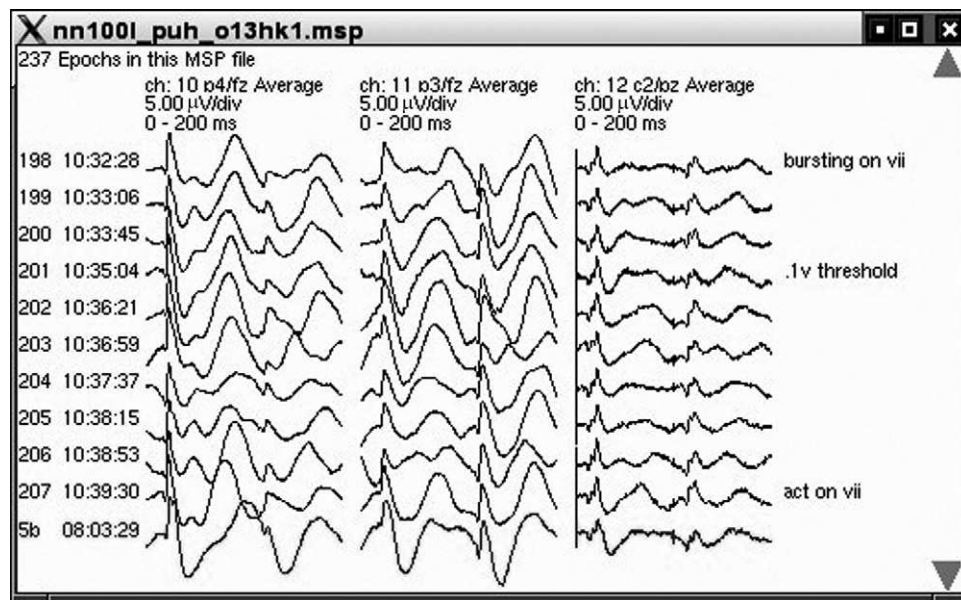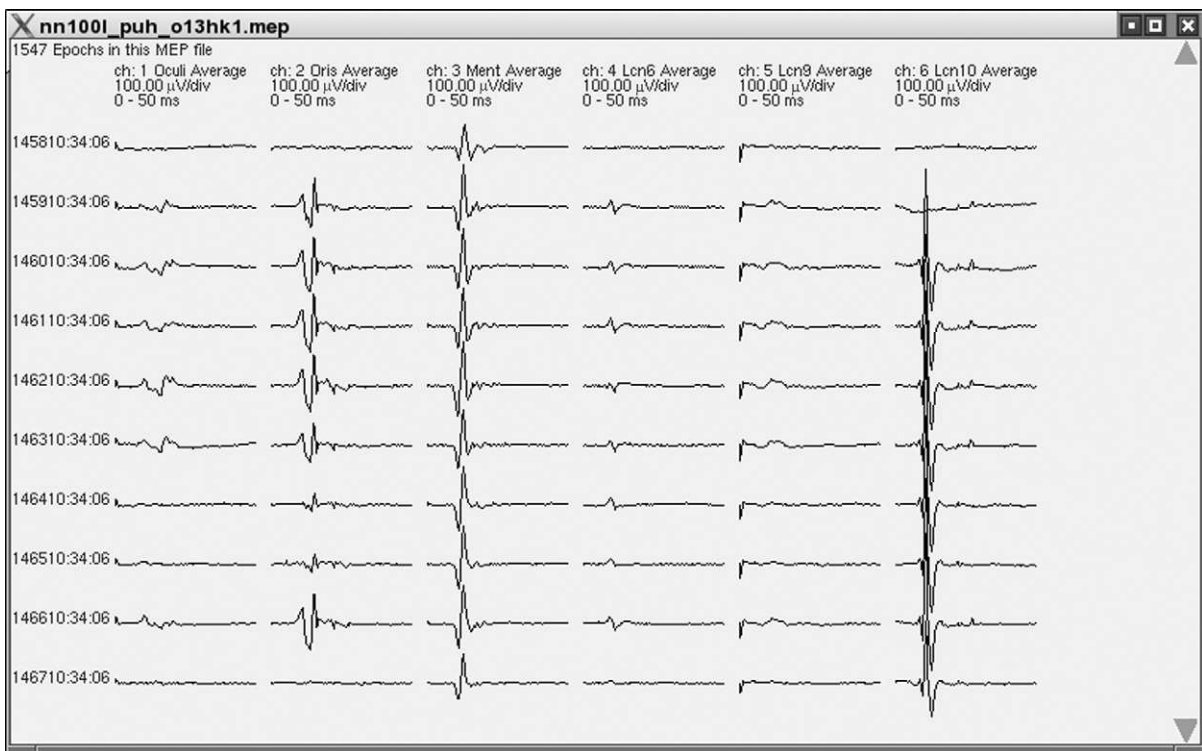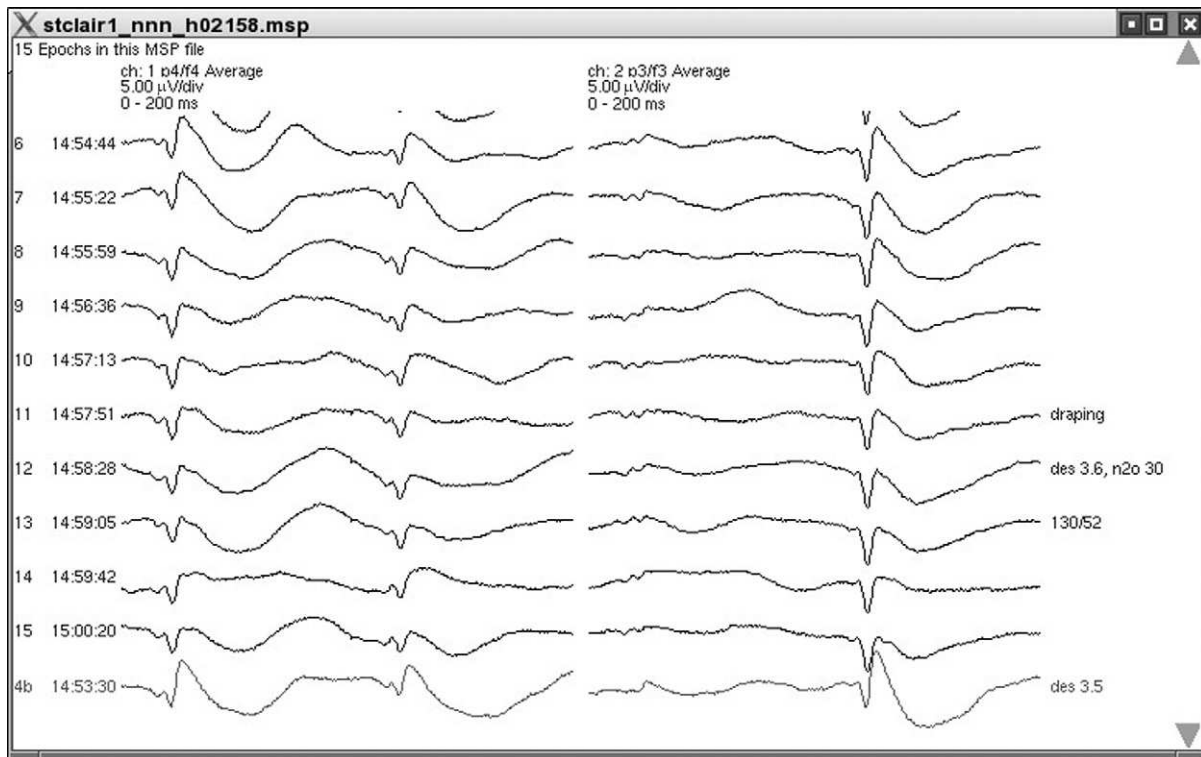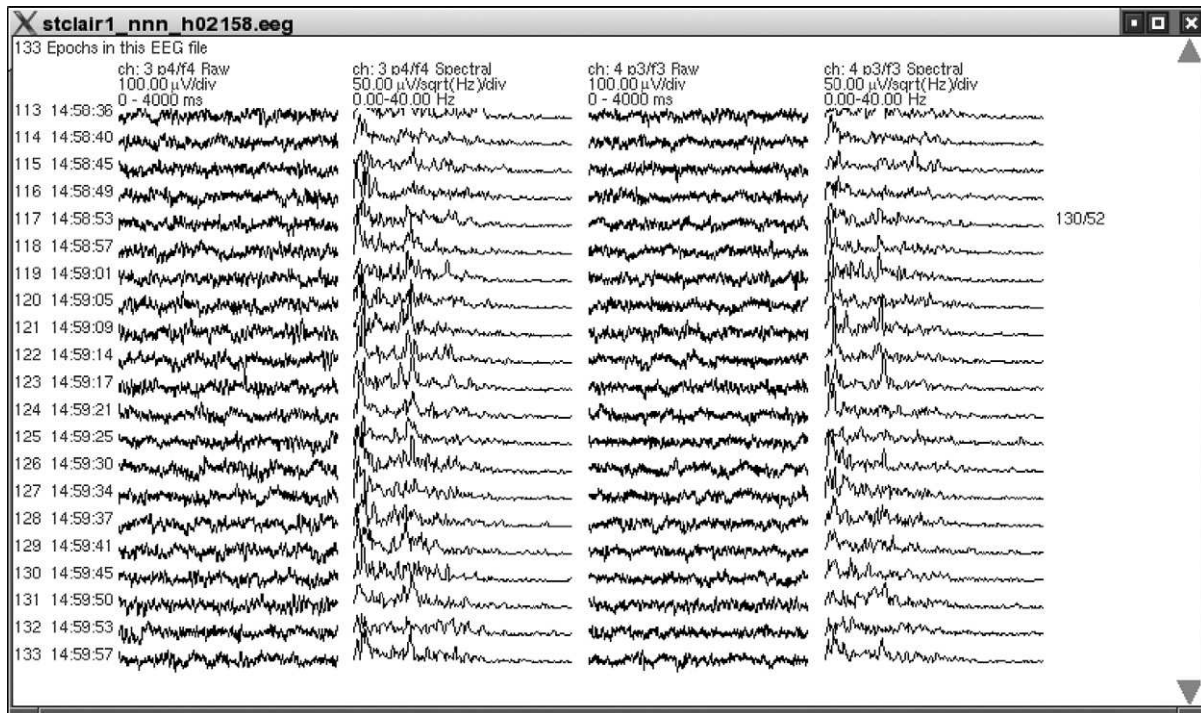

(Fig. 5 continued)

C

D

Fig. 5. Remote data as it appeared on neurophysiologists node in NeuroView from the case whose data is presented in Fig. 1 (NeuroDisplay) and Fig. 2 (NeuroView—local). Note some preferential differences between displays. A: The BAPs are displayed with a 20-ms observation interval and only 10 epochs displayed in the waterfall. B: The MSPs are displayed with a 200-ms observation interval for each frame allowing the right and left stimulus effects to be viewed from each hemisphere. C: presents irritation activity again on the mentalis branch of CN VIII; while D: presents evoked activity predominately from the left CN X and weaker from CN II mentalis and oris branches.
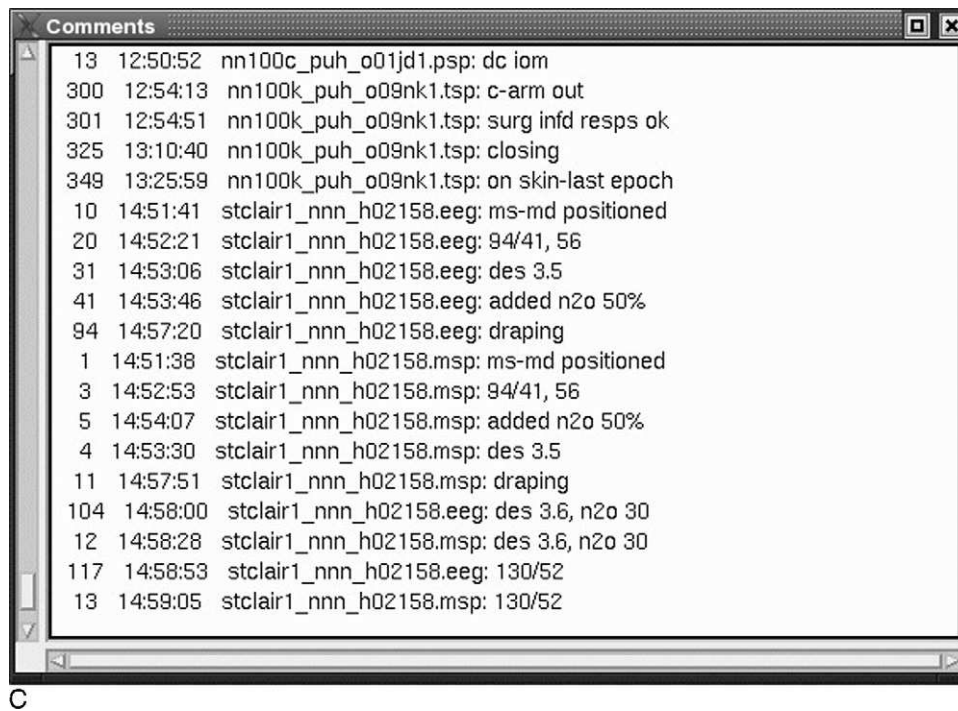
A

B

(Fig. 6 continued)

C

Fig. 6. Remote data from carotid endarterectomy being discussed in NeuroComm window in Fig. 4C. A: presents bilateral MSP data; while B: presents bilateral EEG data with both the continuous EEG and power spectrum being viewed remotely. C: presents another communication tool to facilitate the remote neurophysiologists being aware of all aspects of the cases he is responsible for. What is displayed in this Comments window are all appended comments by the neurotechnologists for the cases for which that individual is responsible. Picking a particular row, for example the third from the bottom, the number 12 refers to the 12th epoch, the time, the data acquisition node, and the comment (reference Fig. 6A for comparison). This window is automatically updated and each time a commented is appended to any data epoch for which that neurophysiologists is responsible.

information necessary to update the Display shell with information. This information is stored in a "'stack" of structures, one structure per display shell. The context of a shell is similar to the context of a process; when one shell has an operation affecting it, the other shells have their states stored and are unchanging. By accessing various elements on the stack, NeuroView quickly and efficiently updates the real-time displays, each with different parameters, utilizing the same routines. NeuroView data may also be accessed across phone lines, via phone dial up, for remote viewing on PCs. For example, all the members of the center for clinical neurophysiology (CCN) have the capability of accessing any activity on NeuroNet from home, allowing them to consult on cases late at night.

The Data Reader is a process that resides on the computer node where the Neuro process is executed. It acts as a disk server that accepts calls requesting NeuroNet data, reads information from disk, and returns it to the calling process. This is a "read-only" process, and does not return patient identifiable information.

33.4. Summary

The commonly accepted principal goal of intraoperative monitoring is to prevent morbidity, and at a certain level this is true; however, the more fundamental goal of intraoperative monitoring is to provide the surgical team with information that allows them to accomplish the desired operative objective with as optimal a surgical strategy as possible, while having a clear idea of what surgical morbidity is being induced along the way.

We conceive of monitoring as placing a real-time feedback control loop around a dynamic, changing system comprised of the surgeon and the patient. This requires a strong commitment to the concept that the central nervous system of the patient is highly sensitive to the operative manipulations of

the surgeon and that appropriately observed variables may predict, and if appropriately interpreted prevent, lesions about to develop. This information permits the surgeon to dynamically modify his approach to the operation and thereby minimize the degree of morbidity induced in the patient.

Stringent time constraints exist in intraoperative monitoring of neurophysiologic function, and damage to the central nervous system may occur rapidly. This constraint has inspired the development of methods for extracting and analyzing evoked potential, EMG, and EEG waveforms rapidly and efficiently. A corollary of the increased sensitivity required to decrease the monitoring time is a higher rate of individually false-positive measures. These are usually, rapidly identified as such and produce no disruption in the flow of the case.

In support of the intraoperative monitoring of these measures, we have developed a distributed computer system, NeuroNet, specifically configured to support the considerations discussed in this chapter. This system provides both off-line and real-time signal processing and data review capabilities, and it addresses many of the problems associated with the acquisition, processing, and display of multivariate neurophysiologic data in these complex cases.

It cannot be emphasized enough that the measures utilized be both specific to the neural tissue being manipulated and sensitive to changes in the functioning of the neural tissue produced by the surgical manipulations. These measures must be obtained, displayed, and interpreted simultaneously permitting a multidimensional assessment of the integrity of the neural structures at risk.

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