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A flexible PC-based physiological monitor

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Abstract

We have developed a flexible physiological monitoring and analysis system for physiological studies in which data are obtained over extended periods. Our system uses low-cost personal computer hardware to concentrate data from existing multiple monitoring devices. All monitored parameters are displayed on a single screen and recorded in a single file. The system automates the process of physiological record keeping by providing continuous displays of vital signs. In addition, audible and visual alarms are produced when vital signs are outside of acceptable ranges, prompting the experimenter to take corrective actions. The central element of the system is a program running in a dedicated manner on an IBM PC compatible computer. The program is written in C and makes use of a graphics library to display traces and analysis results in real time on any standard display for the PC. This program assigns the analog channels of an

A/D board to particular physiological parameters by initially reading a configuration file, which also describes the alarm conditions and analysis routine for each parameter. All hardware specific code is isolated into well defined modules. The program is both highly flexible with regard to different sets of parameters and highly portable for different experimental and computer environments.

Introduction

Physiological experiments using animals, particularly those in neuroscience, often require close attention to experimental conditions over extended periods of time, sometimes several days. Complicated surgical and experimental procedures can distract the researcher from the physiological condition of the animal. In addition, protocols may constrain the ability to keep detailed records of physiological variables. Indeed, even in hospital situations, manual record keeping of anesthetic state often fails to meet medical and legal standards (Gage et al, 1990). In physiological experiments using mammalian animals, the quality and reliability of the experimental data depend critically on the physiological condition of the animal. Therefore, this alone is sufficient reason to maintain the animal's physiological parameters as stable as possible. Furthermore, good record keeping of the animal's physiological state is often a requirement of institutions to make sure that proper care of the animal has been maintained throughout the course of an experiment. However, frequent writing down, by hand, values of physiological parameters can be tiring and interferes with the attention needed for the experiment itself. One solution to this problem is computer-assisted monitoring of the physiological state of the animal with automated collection, analysis, recording, and a mechanism to alert the experimenter of possible problems whenever they arise. In addition, records can also prove useful in interpreting experimentally acquired data in the context of physiological state.

Unfortunately, commercial monitors providing these features are traditionally available only in a medical context for use with humans, are very expensive, and are not easily customized (DeVos et al., 1991). Usually, physiological data are provided by independent monitors which preclude quick assessment of all physiological variables (Phelps and Goldman, 1992). We have addressed these problems by constructing a flexible and low-cost monitoring system capable of real-time analysis and display of physiological signals.

The system can make use of all existing monitoring devices that provide analog voltage outputs. The central element of this system is a program that runs in a dedicated manner on an IBM PC compatible computer. This system has significant advantages over traditional monitors because the complete physiological records of an animal are kept in a single file for convenient access and the system notifies the experimenter with a voice alarm if any parameters are outside the normal range. Both the automatic recording of physiological parameters as well as voice alarms have proven very effective in minimizing errors in hospital environments (DeVos et al, 1991; McIntyre and Nelson, 1989). Additionally, the program provides for the menu-driven insertion of comments into the physiological record at any time during the course of the experiment. The program also requests human verification of the physiological record at regular intervals by audibly calling out the experimenter's name. The system therefore provides a complete record of the physiological state of an animal, documents all procedures, such as drug administration, that are performed during the course of the experiment, and documents the experimenter's attention to the physiological state of the animal. Complete reports of physiological parameters, procedures performed, and verification records may be produced at any time, including the graphs of the parameters being monitored.

Design

Design Goals

The following features are deemed necessary and desireable based on our experience in acute neurophysiological experiments on central visual pathways of the cat. All of the design goals listed have been achieved. Reasons for these goals and details of their implementation are given below in roughly the order listed.

* Use of readily available hardware and software components, including the use of existing monitoring equipment.
* Flexibility for adding new monitoring parameters without modification or recompilation of the program code.
* Waveform displays for rapidly varying signals such as the EEG (electroencephalogram) and the ECG (electrocardiogram).
* Extraction and display of a single descriptive value from each sweep of waveform display, e.g., EEG amplitude and heart rate from EEG and ECG, respectively.
* Numerical value display for slowly varying signals such as body temperature and end-tidal CO_2 level.
* Visual and voice alarms when a parameter goes beyond upper or lower limit, with announcement of the name of the parameter and its current value.
* Automatic logging of all parameter values to a file at specified time intervals.
* Periodic requests for verification of physiological parameters and logging of verification process to comply with anticipated institutional requirements.
* Insertion of comments into the record file, for noting drug administration details and other performed procedures.
* Record file format that is both human and machine readable.
* Optional capability to maintain two copies of the record file on separate computers via network for backup.
* Capability, via a separate program, to generate a summary report from the record file, including graphical plots of the time course of each parameter.

Hardware

The hardware for the physiological monitor consists of an IBM PC compatible computer running MS-DOS with a multi-channel A/D (analog-to-digital converter) board (PCL-812, B&C Microsystems) (Figure 1). The A/D board has a programmable timer used to trigger A/D converters at a desired sampling rate, an A/D converter and a 16-channel multiplexer. Optionally, an Ethernet card is installed to provide remote data backup, voice alerts, and viewing of physiological records during experiments via other computers on a network. External signals from physiological monitors are fed into the A/D input channels. In our current set-up, we monitor signals from a CO_2 monitor (Hewlett-Packard 47210A Capnometer), a rectal probe thermometer (Sensortek BAT-12 and RET-1), and electroencephalogram (EEG) and electrocardiogram (ECG) amplifiers (custom built). Additional signals may be monitored up to the limit of 16 channels.

For each analog input channel for which the waveform of the signal is displayed, the A/D converter samples the signal at the rate of 200 samples/sec. This is sufficient to capture the salient features of the ECG and EEG signals. Because the A/D converter itself can sample at a rate up to 30,000 samples/sec, the primary limiting factor in the sampling rate is the speed with which the continuously updated traces can be drawn. Considerably higher sampling rates should be possible using assembly language code optimized for particular graphics boards. However, such code would compromise the portability of the program between different PC platforms. Higher sampling rates can also be attained through the use of higher speed computer and graphics sub-systems. In our laboratory, 200 Hz sampling of two channels is easily maintained with a 6 MHz PC/AT with a standard EGA card. Practically all PC configurations currently available commercially

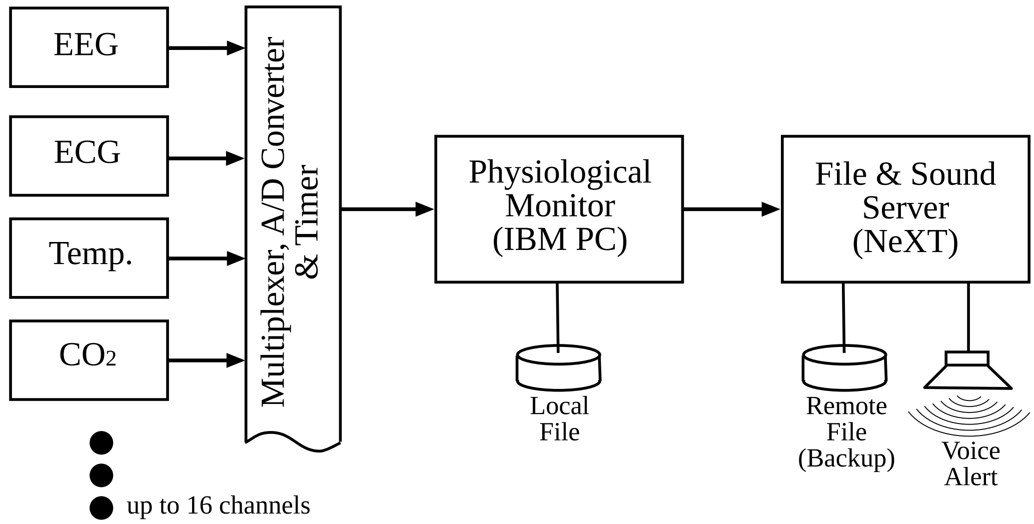

Fig. 1 A block diagram is shown for the physiological monitoring system we employ (see text for details).

exceed our configuration by a large margin. This is due to the fact that we are recycling old equipment which is not desirable for use as a desk-top computer.

The physiological monitor, as it is implemented in our laboratory, relies on an Ethernet link to a NeXT computer for the backup storage of physiological data and for the production of voice messages. Neither of these functions is hardware specific for the NeXT. The file and voice server functions of the NeXT may be duplicated easily by other types of computers. File backup can be achieved through any networking architecture. For example, the following systems could be used: NetWare (Novell), a PC implementation of NFS (Network File System), or a Unix remote shell (rsh) client via a TCP/IP connection. Audible messages may be generated on the PC itself locally, or on any Unix machine with sound output hardware.

The audible messages are digital voice recordings which are played at times specified by the SCOPE program. The audible message system can be easily implemented on any of the sound cards available for the PC. The primary advantages of a networked system such as depicted in Figure 1 are the presence of a backup copy of the record file on another computer and the capability to generate detailed reports even during an experiment. However, the system is designed to be usable in its least sophisticated hardware configuration: a single PC (AT or faster) equipped with an A/D board and a sound board.

To protect the system from power outages, uninterruptible power supplies (UPS) are used to ensure a continuous supply of electrical power at all times. In addition, the entire building is served by a backup generator that will be started automatically in the event of power outages longer than several seconds.

Software

The main program, titled SCOPE, is written in the C language. It analyzes, displays and records data acquired via A/D converters from external monitoring devices. Three external programs, APPENDLN, SAY_THIS, and CHK_DIR, are executed from within SCOPE. The experimenter, therefore, does not have to be aware of these external programs. The programs help in the modular design of the software by isolating functions that must either rely on a remote computer via the network, or be implemented locally on the same PC running SCOPE. In this way, differences in network configurations may be absorbed by the external programs without affecting the design of the main program.

APPENDLN is used to append a line of text to a file that is located remotely via the network. SAY_-THIS is a command that vocalizes a message given as an argument. The command either generates the speech on the local machine or forwards the command to a remote computer. CHK_DIR is used to check if the data directory exists on a remote machine, and whether files may be created in the directory and written to. This is necessary to guarantee that data can be written to a remote file, since many network and Unix operating systems enforce strict schemes of file protection.

Upon starting, SCOPE requests the name or identification of the animal being monitored. This name is used to specify a unique file for storing the acquired data. Existing records for the same animal are untouched and new data are appended to the end of the file every time the program is restarted. Global settings for the monitoring session are also set during initialization. These settings include the rate at which SCOPE samples the analog channels, and the time intervals of verification by the experimenter. Network parameters for communication to the remote computer are specified in DOS environment strings. Each analog channel is set up according to parameters specified in a text file (the *parameter file*) that is read by SCOPE upon start up. Because all analysis options and parameters are specified in this editable file, the system is highly flexible for different sets of physiological signals. For example, in our laboratory, analog signals from four external devices are fed into the A/D board: ECG, EEG, expired CO_2, and body temperature (Table 1). It is

Table 1 - Parameter File

#	Mode	Color	Analysis	Gain	Offset	AlmMin	AlmMax	AlmInt
ECG	waveform	yellow	ppm	1.0	0	140	280	30
Temp	sample	cyan	*	-0.25	7.5	37	39	600
EEG	waveform	green	rms	0.82	0	1	30	600
CO2	sample	magenta	*	0.125	0	28	35	10

Note: ppm stands for peaks per minute, and rms for root mean square. AlmMin, AlmMax, and AlmInt represent lower and upper bounds for alarms, and alarm intervals in seconds, respectively.

also possible to monitor non-physiological parameters such as the amount of oxygen remaining in a tank given an appropriate pressure-to-voltage transducer, and to trigger an alarm when the oxygen level gets too low. Channels can be monitored in two ways: waveform or end-sweep sampling. Channels with waveform monitoring are displayed in a manner analogous to that of a storage oscilloscope. For end-sweep sampling, a sample value is acquired from each channel and displayed numerically at the end of a waveform display. As a general rule, waveform monitoring is used for rapidly varying signals such as the EEG and ECG. End-sweep sampling is used for signals that change slowly, e.g., body temperature.

A parameter file is used to configure the SCOPE program so that data from each channel of the analog input are displayed appropriately. The file also stores various display options and calibration information necessary to match a numerical display to the actual value of the monitored parameter. By employing this setup, a wide variety of external monitoring devices, each with possibly different output voltage ranges, may be connected without modifying the SCOPE program itself. The calibration of each channel can also be achieved easily.

The parameter file is formatted according to the manner specified in Table 1. Each line of the file specifies parameters for one analog input channel. The row position in the file determines the channel number, e.g. the first line of the parameter file describes channel #0 of the A/D board input. Each channel can have a distinct display color for numeric and waveform data to highlight the distinction between different physiological variables (DeVos et al., 1991). The two monitoring options for each channel are waveform and end-sweep sample value. For waveform display, the channel is displayed in a manner similar to a storage oscilloscope, with a numerical display of the key descriptive parameter extracted from the waveform. For example, we extract from each sweep of ECG and EEG waveforms the heart rate and EEG amplitude, respectively. To obtain the heart rate from the ECG, we use a peak detection algorithm and compute the average interval between heart beats. The inverse of that is then computed. Analyses are performed at the end of each trace. In the current program, the following analyses are available: mean value, peak value, RMS (root-mean-square) value, peaks/min, and spectral power within the pass-band of 5-10 Hz. The choice of the analysis method depends on the nature of the signal and how the value we are interested in is expressed in the waveform. For example, if the intratracheal pressure is monitored for detecting a clogged trachea, the peak value is the most appropriate analysis method to use. On the other hand, if the rate of breathing is more important than the peak tracheal pressure, peaks/min analysis should be used. For measuring the activity level of random signals such as the EEG or the electromyogram, RMS analysis may be most suitable. The list of analysis options is not complete obviously, but should a need arise for a new method of analysis, it may be added quite simply by writing a single C function. For end-sweep display, the value of the input signal at the end of a waveform sweep period is displayed numerically. For both end-sweep and waveform display channels, the SCOPE program converts analog voltages ($\pm$5 volts) to parameter values according to the gain and offset parameters specified in the parameter file. End-values are displayed above the continuous traces in colors specified in the parameter file. Calibration of each channel is achieved by the gain and offset parameters. Since an input sensing device usually has its own calibrated display, as our CO_2 meter and thermometer do, each channel of the monitoring system is calibrated to produce values matched to those of the sensing device. The stability of the calibration depends primarily on that of the original sensing device and the quality of the A/D converter in the monitoring system. For our system, a recalibration was needed for the temperature channel after about a year of operation, but other channels have remained stable.

Figure 2 shows an actual screen capture of the SCOPE program monitoring the physiological state of an anesthetized and paralyzed cat. The two horizontal traces represent ECG and EEG, as labelled on the

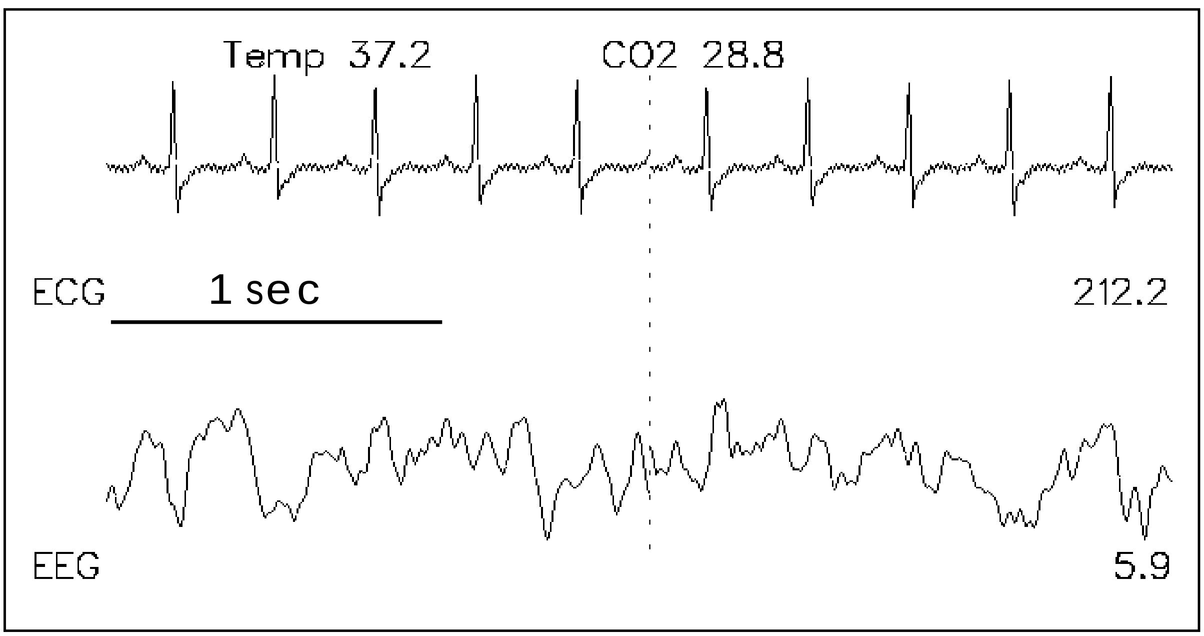

Fig.2 A screen capture is shown of the monitoring system. The two waveforms represent electrocardiogram (ECG) and electroencephalogram (EEG) data for the top and bottom traces, respectively. Numbers at the right indicate the heart rate and the EEG amplitude extracted from the respective waveforms. The dotted vertical line indicates discontinuity in the waveforms between the new samples and the previous sweep. The dotted line and the horizontal time scale line (1 sec) are not present in the actual display.

left. The vertical dotted line (not present on the actual screen) represents the discontinuity between the most recent sample and the oldest sample of the last sweep. New waveform samples are displayed immediately as they are acquired replacing the old value. Therefore, the discontinuities appear to sweep from left to right. To the right of these traces are their analysis values, the heart rate (beats/minute) and the EEG amplitude (root-mean-square value in ùV), respectively. The two channels which are displayed only at the end of the each sweep are along the top of the screen. The body temperature is displayed in units of degrees Celsius, while expired CO_2 is displayed in units of mmHg. In the current system, the program detects the screen size in pixels, and uses all available screen area. Each waveform sample occupies one horizontal pixel. Because analysis results (such as beats/minute for the ECG and EEG amplitude) are displayed to the right of the traces, the number of horizontal pixels available for drawing traces is slightly less than the horizontal resolution. Thus each sweep roughly lasts a period of time equal to the horizontal resolution divided by the sampling rate. For our sampling rate of 200 samples/sec and approximately 500 pixels available for the waveform, each sweep represents 2.5 seconds. Although the program can run on a monochrome monitor, a color monitor is desirable so that physiological parameters can be distinguished by color. This also allows a quick determination of whether a visual alarm is present for out-of-range parameters.

Visual and voice alarms are generated when one or more of monitored parameters go out-of-range to draw the attention of the experimenter who might be occupied in other tasks at the time. The acceptable range of each parameter is bounded by the upper and lower limits specified in the parameter file for that channel. For the waveform display, this range applies to the analysis value; for end-sweep display, to the sample value. When a parameter is outside of the acceptable range, SCOPE issues an audible warning announcing the parameter and its current value. SCOPE also displays the out-of-range value in red. Because certain parameters, such as body temperature, require time before experimenter modifications can effect changes, there is an alarm interval for each channel that specifies the shortest permissible interval between audible alarms. For example, in our laboratory the alarm interval for body temperature is 180 seconds. This means that once an audible body temperature warning is made, another warning will not be made regarding body temperature for at least another 3 minutes. This alarm interval applies only to audible messages. Out-of-range parameter values are always displayed in the color red.

Physiological records are logged to a disk file at regular intervals by SCOPE. Table 2 is a short segment of the physiological record of an anesthetized and paralyzed cat taken every 5 minutes. Each record

Table 2 - Record File (excerpt)

>Time	EEG	ECG	Temp	CO2	
Thu Oct 06 19:54:10 1994	257.31	5.23	37.90	33.38	
Thu Oct 06 19:59:13 1994	259.46	4.93	38.15	33.75	
Thu Oct 06 20:04:15 1994	236.56	4.99	38.15	32.25	
>Eyes and Lenses Cleaned (Thu Oct 06 20:05:01 1994) by: io					
>Atropine and Neosynephrine Drops (Thu Oct 06 20:05:10 1994) by: io					
>Optics still clear ! (Thu Oct 06 20:05:30 1994) by: io					
Thu Oct 06 20:09:25 1994	256.68	4.81	37.65	31.88	Verified: io
Thu Oct 06 20:14:28 1994	257.60	6.61	37.90	31.25	

is a line of text that is always appended to the end of a file, and consists of date and time, and several numerical values of monitored parameters. In our case, the EEG amplitude, heart rate, temperature, and end-tidal CO_2 level are recorded. Two instances of verified records are also shown. Comments are also inserted into this file preceded by the ">" character at the beginning of a line. Comments are used to record procedures performed on the animal, such as cleaning of contact lenses, application or injection of drugs and their doses.

Experimenter initials, included during verification and when comments are made, appear at the end of lines. Each comment is also time and date stamped and notes the experimenter's initials. To insert comments or to change settings of the SCOPE program, the experimenter may press any key on the PC at any time. After the completion of a sweep during which a key was hit, a control menu appears on the PC screen. Selecting an item from a list of routine messages causes insertion of the corresponding message into the record file. It is of course possible to insert arbitrary text as a comment.

Optionally, SCOPE is able to keep a backup copy of the file on a remote computer via the network at all times. This not only protects against accidental loss of important data, it also allows detailed examination, on a remote computer, of the history of physiological parameters for the animal at any time including times during the experiment. For example, interim reports may be generated without interrupting the monitoring process. This remote file backup is achieved by SCOPE executing an external program APPENDLN with a line to text as an argument. With this modular design, it is possible to accommodate a variety of network configurations by using an appropriate version of APPENDLN tailored for each network, without modifying the SCOPE program itself.

The system periodically prompts the experimenter to check the current physiological state of the animal by calling out the experimenter's name followed by the audible message "Please verify." The name of the experimenter is known to the system because the experimenter checks in to the system by entering his or her initials from a menu option. Sound files containing names must have been prepared before use. The message "Please verify" is also displayed by SCOPE on the PC screen. Upon a key press by the experimenter, it records the fact that the experimenter responded to the prompt in the file along with the current values of the parameters. This feature is implemented primarily to satisfy a requirement specified by local animal care and use guidelines. Such verification also ensures that the automated recording of physiological data does not reduce the vigilance of the experimenter towards the state of the animal (Yablok 1990). There are three time settings regarding this verification which are set by the experimenter when SCOPE is started up. The first is the standard interval between verification requests. The second is the period of time that SCOPE should wait for verification before reverting to its display/analysis mode. The third setting is the amount of time that SCOPE should wait before requesting a verification again if no verification was received. In our laboratory, we set these values to 30 minutes, 60 seconds, and 5 minutes, respectively.

The voice messages are constructed from segments of digitized voice representing words and phrases. This scheme obviously limits the vocabulary since messages can only contain pre-recorded words and phrases, but the quality and legibility of the generated speech is generally far superior to that generated by text-to-speech synthesis which may have unlimited vocabulary. Fortunately, the limited vocabulary is not a serious limitation for this application. A collection of sound files has been created which contains necessary words and phases (including names of experimenters). These files contain concise and appropriate messages, such as "Check the expired carbon dioxide." in file check_CO2.snd. The actual value of the parameter is then announced. Numerical values sent by SCOPE are parsed by the NeXT into words. For example, 123.8 becomes "one hundred twenty three point eight." Sound files have been prepared containing all the words necessary to announce numbers less than one million ("point", 0 through 20, 30, 40, 50, 60, 70, 80, 90, "hundred", and "thousand"). Thus, for the parameter 123.8, the sound files one.snd, hundred.snd, twenty.snd, three.snd, point.snd, and eight.snd are played sequentially. If multiple warnings are applicable, they are announced sequentially. Sound signals are sampled with a resolution of 8 bits/sample at 8.012 kHz with a non-linear mu-law encoding which is used in standard digital telephone systems. The mu-law encoding achieves a higher signal-to-noise ratio than the linear 8-bit digitization. For this limited vocabulary application, the sound files occupy a total of only 500 kbytes of disk space.

The speech generation program SAY_THIS is a simple command program which takes a list of sound files as an argument. The SCOPE program executes the speech program as a separate process. The following command line is constructed by SCOPE, and it generates a message "Check the expired carbon dioxide. Thirty seven point five."

SAY_THIS "check_CO2 #37.5"

A speech of any length may be created by listing as many sound files as needed. Numbers are treated specially by preceding each number with the character '#' indicating that the following item should be vocalized as a number.

As mentioned above, such sound files could also be created for the sound boards readily available for PC compatibles. If a sound card is placed in the PC running SCOPE, then the SAY_THIS command on the PC must be responsible for parsing the list of sound files and addressing the sound hardware. Alternately, the SAY_THIS program could simply forward the command to a remote computer via the network. Because the speech generation is implemented as a separate program which gets executed by SCOPE, one can change the location of sound generation hardware by simply substituting the command on the PC without modifying the SCOPE program itself. As with the logging of data and comments, this modular design makes the structure of SCOPE simple and allows flexible reconfiguration of hardware components.

Results

Sample results for cat kd214 are shown in Fig. 3. Included are plots of the expired CO_2, the heart rate, body temperature, and the RMS amplitude of the EEG contained in the record file (see Table-2) against time. The graphs are produced by a program written for the NeXT computer. These variables were recorded every five minutes during the 4 day period of the experiment. During surgery, ECG and rectal temperature were monitored but EEG and expired CO_2 were not monitored because their sensor attachments interfere with the procedures. Later, after paralysis was induced, all parameters were measured. Figure 3 demonstrates that a steady physiological state was maintained throughout the course of the experiment. It also details the exact changes that took place in the four monitored variables over a four day period to a degree not feasible with manual recording methods. For example, small periodic variations are clearly visible in the temperature record. This variation is the consequence of the feed-back temperature control unit we use that switches a heating pad and a heat lamp on and off. The heart rate was approximately 150 beats/min during surgery, and it rose to about 260 beat/min after paralysis was induced with gallamine triethiodide (Flaxedil) and maintained at 10 $mg \cdot kg^{-1} \cdot h^{-1}$ by continuous infusion. After paralysis, anesthesia was maintained by the continuous infusion of Surital(1 $mg \cdot kg^{-1} \cdot h^{-1}$) supplemented with N_2O (70%) delivered by artificial respiration in a mixture with oxygen (30%).

Conclusion

We have developed a flexible physiological monitoring system for animals designed for use in short-term or extended experiments. The system has been implemented in a low cost manner by using a PC and existing monitoring devices already available in a typical laboratory. The benefits of this system are quite substantial. The continuous monitoring combined with visual and auditory alarms help in maintaining very stable physiological conditions of the animal. It can also prevent a possible loss of the preparation that may result from accidents, equipment malfunction, and temporary lapses of attention on the part of the experimenter. Furthermore, the automatic record keeping and periodic prompts for verification aid in complying with local animal care and use guidelines. We have used this system for about a year, and find ourselves completely dependent on it.

One other point should be noted. Our system is ideally suited for short or long-term studies of correlations among different physiological and other non-physiological parameters. For example, one may use

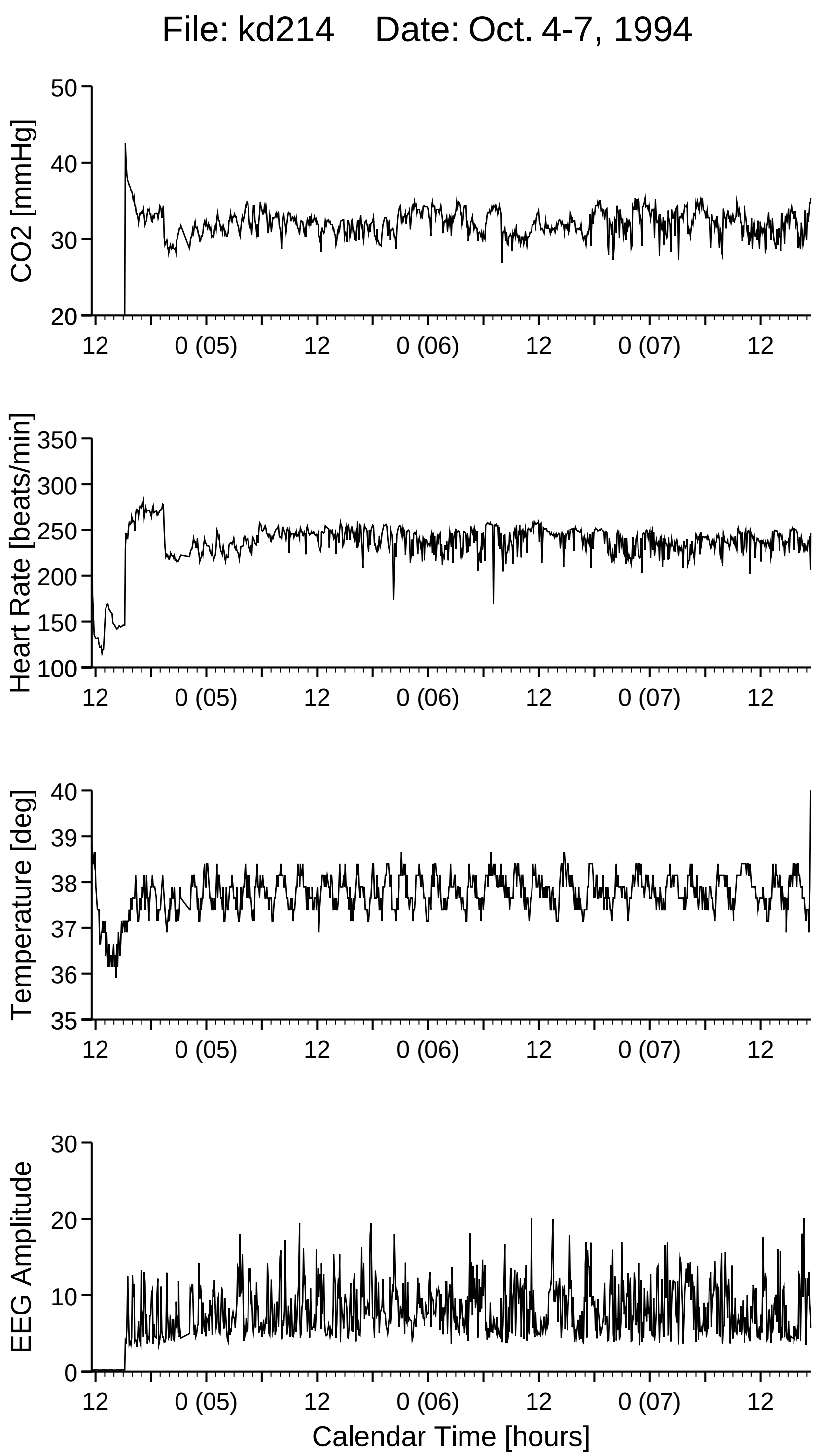

Fig. 3 Plots are shown for the four physiological parameters monitored throughout a 4-day experiment on a paralyzed anesthetized cat. The end-tidal carbon dioxide, heart rate, body temperature, and EEG amplitude are shown against calendar time. Numbers in brackets for zero hours along the horizontal axis denote the day of the month. Plots are made automatically by a program running on a NEXTSTEP system from a file containing a total of 970 records. A short segment of this file is given in Table-2.

the system to study effects of changing gas mixture ratios used for respiration or drug injections on various physiological parameters using appropriate sensors for each parameter. Finally, the system we describe here allows an experimenter to determine if poor physiological status might have contributed to particular experimental results.

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References

DeVos, C.G., Abel, M.D., and Abenstein, J.P. (1991) An evaluation of an automated anesthesia record keeping system. *Biomedical Sci Instrumentation,* **27**:219-225.

Gage, J.S., Subramanian, S., Dydro, J.F., and Poppers, P.J. (1990) Automated anesthesia surgery medical record system. *Int J Clin Monitoring and Computing,* **7**:259-263.

McIntyre, J.W.R., and Nelson, T.M. (1989) Application of automated human voice delivery to warning devices in an intensive care unit: A laboratory study. *Int J Clin Monitoring and Computing,* **6**:255-262.

Phelps, E.B., and Goldman, J.M. (1992) Automated situational analysis for operating room anesthesia monitoring. *Biomedical Sci Instrumentation,* **28**:111-116.

Yablok, D.O. (1990) Comparison of vigilance using automated versus hand written records. *Anesthesiology*, **73**:A416.