Chapter 13

Towards a comprehensive technology for recording and analysis of multiple physiological parameters within their behavioral and environmental context

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Introduction

Ambulatory psychophysiological monitoring opens the possibility of studying physiological reactions in the natural environment of the individual person. For a comprehensive research strategy, this implies both the adequate recording and analysis of physiological and environmental variables as well as the synchronous assessment of emotional and behavioral factors. Such a goal sets high demands on the technical equipment.

This paper mainly deals with the developments that we undertook to realize a technology and methodology for the combined recording and analysis of physiological variables within their behavioral and environmental context.

Unsatisfied with existing measuring devices, we started the development of a multi-channel ambulatory recording system in 1988 (Stephan, Mutz, Langer, Schmitz & Wemschulte, 1989). Major concerns were flexibility in the combination of channels and in the selection of sampling rates, possibilities of data reduction during sampling and costs of the system. This resulted in the "Vitaport 1" recorder and the "Vitagraph" software to perform some elementary data analysis; further data analysis was thought to be more appropriately handled by statistical packages such as SPSS; this development is discussed in Chapter 2.

Given the rapid technological evolution in storage media, processor technology and portable hand held computers, a mass-storage physiological recorder and analyzer, called "Vitaport 2", was developed as a logical next step. The communication with external hand held computers to allow for elaborate self-reporting in the form of a digital diary, as well as a new concept for data analysis and reduction are discussed in chapter 3. In Chapter 4 we highlight some applications of the various components of the system. First we report on a study on cardiovascular reactivity carried out as a laboratory-to-field comparison with Vitaport 1. In-home monitoring of sleep with full polysomnographic facilities is a medical application, where the functionality of the Vitaport 2, as well as the data analysis features can be well illustrated. Finally, we report on the latest development in accelero sensor technology that allows for cost effective simultaneous detailed monitoring of both postures and various categories of movemental activity.

The beginnings: Vitaport 1

The measuring device

The Vitaport 1 is a physiological recording device, which allows the recording of multiple physiological and physical variables under ambulatory conditions. Its 16 channels are optimized for the different properties of the various physiological signals commonly assessed in psychophysiological research. It can be used for a wide range of applications. Examples are studies on stress at the workplace (Jain, Stephan, Gediehn, Ottow, Petersen, Seck & Mutz, 1993), the situational context of psychosomatic symptoms (Stephan, 1990), effects of nicotine under laboratory and field conditions (Mucha, Mutz & Stephan, 1992; Weiss, Mucha, Mutz & Stephan, 1994), laboratory-to-field comparisons of cardiovascular reactivity (see “Some Applications”) or media research, in which physiological reactions of spectators or actors can be investigated (Bente, Stephan, Jain & Mutz, 1992).

Due to its small size (13 x 9 x 3.5 cm) and weight (about 500 g) the device can easily be worn at any place (e.g. at work, at home) and during various activities. Most subjects reported that the measurement interfered little with their usual activities and many forgot about the system after a short adaptation period. Of 30 police officers who carried the system during their normal work on two consecutive days, only two (7%) said they felt uncomfortable, while 17 (57%) said that there was no or only minimal discomfort.

The device allows the recording of up to 16 different physiological or physical signals simultaneously. Thirteen amplifiers are adjusted to measure ECG, EMG (integrated signal), electrodermal activity (EDA), temperature (two channels for body and/or outside temperature), respiration (two channels for excursions of thorax and abdomen), activity (three channels assessed by accelerometer) and 3 universal channels suitable for further bipolar ECG or EMG derivations, as well as for EEG, EOG, etc. A digital input channel can register up to 8 event markers as an on/off signal as well as input from a specially designed keypad (see “Recording of Self-Report data: The Emopad”). Signals of other electronic devices, e.g., a task computer or a tachistoscope, can also be fed into this channel to register important events as well as for synchronization purposes. Two external channels without amplifiers (sensitivity 0 - 2.5 V) can record signals from other systems like a blood pressure or oxygen saturation device.

After amplification signals are A/D converted, they are further handled by a microprocessor for on-line data reduction. Different types of filters can be set according to specific needs. Sampling and storage rates, as well as the type and settings of preprocessing (moving average, high pass, integral, R-R-interval, etc.) are specified by the Vitagraph software on the host computer for each channel separately and are downloaded to the recorder prior to measurement. After preprocessing, data is stored digitally on RAM-cards with a capacity of up to 1 MByte. When data is stored in byte format with a storage rate of 1 hertz, 12 channels can be stored for 24 hours. With faster storage or 12 bit resolution, recording time is reduced proportionately. Memory cards can easily be exchanged in the course of the measurement by any layperson.

The power supply is ensured by rechargeables (360 mAh, 4.8 V) or 4 type micro/AAA batteries. In a standard application with 8 channels sampled at 2 Hz, power consumption equals about 10 mA when EDA is not recorded, and about 15 mA with EDA recording. Thus, rechargeables will last for about 36 hours and 24 hours respectively.

Recording of self-report data: The “Emopad”

For the interpretation of physiological signals, context information regarding the environment, behavior and subjective state of the subjects studied is normally necessary. Some information about objective properties of the environment (temperature, noise) and some behavioral information (activity) can be obtained by the physiological recording system (see “Recent Developments: The recording of Self-Reported Emotional, Behavioral and Situational Data”). For psychological and more detailed situational information, self-report data is needed. Self-reports during ambulatory monitoring can be gathered by paper-and-pencil diaries or by electronic devices. The major advantages of electronic diaries are that the time of the self-report is registered, that the subjects have no access to previous ratings, and that alarm signals can remind the subjects to fill in the diary at fixed or random time intervals (Fahrenberg, 1994; Hank & Schwenkmezger, this volume).

To assess self-rated emotional, situational or behavioral variables, a keypad (15 x 8 x 1 cm) was developed, which is controlled by the Vitaport via a serial link (Jain, Mutz & Mucha, 1992). It consists of 3 lines of 16 keys each, meant for 3 rating scales and another 7 buttons for single items plus an “OK” button to turn the alarm off. LEDs and a sound can be programmed to activate after fixed or random time intervals or dependent on a physiological signal above or below a certain threshold. Each key is assigned to a certain value, which is stored when pressed in a separate channel of Vitaport. Within the Vitagraph program a meaning (text) can be assigned to each of these values.

Originally, the keypad (“Emopad”) was designed for ratings on the Self Assessment Ma-

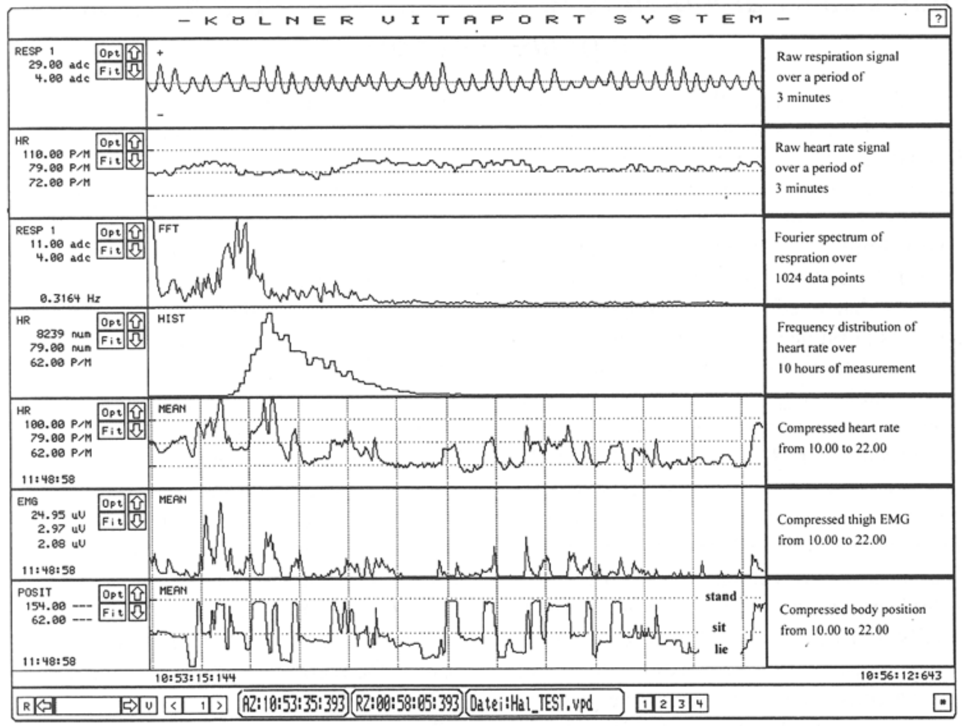

Figure 1: Example of data displayed in Vitagraph with some statistical results

nekin (Hodes, Cook, & Lang, 1985). It consists of three rating scales graphically depicted, which are meant to assess the three underlying factors of emotion, namely valence, arousal and dominance (Russell & Mehrabian, 1977). By fixing a paper with different texts or graphics to the keypad, the 55 buttons can be used flexibly for different questionnaires.

Data display and analysis: Vitagraph

All the recorded Vitaport data is displayed graphically within the Vitagraph software. The recorded variables can be displayed in any combination of up to 16 channels (signals) per screen. Normally, individual data points are represented by individual pixels. Different time resolutions can be chosen by compression factors of 2, 4 and 8. Finally, the whole recording period can be compressed to one page, including some summary statistics. Various statistical functions (histograms, averaging over different time periods, fast fourier transform, compressed spectral arrays) are available. It is beyond the scope of this paper to describe the complete functionality of the software. Figure 1 shows an example of data displayed in Vitagraph and of some of the statistical functions.

Recent developments

High quality ambulatory recordings of multiple physiological signals: Vitaport 2

Further development of the recording device was driven by the need to obtain high quality multi-channel EEG recordings over several hours and was linked to new advances in microelectronics. The storage capacity of Vitaport 1 was very limited (1 MByte) and therefore recording of longer time periods was not possible for signals that need high sampling rates. Although it is possible to derive valid information from composite measures of EEG sampled at low frequencies, e.g. to classify sleep stages and derive global measures of sleep continuity (Mutz, Mucha, Jain & Stephan, 1993), detailed and accurate analysis is not possible. Moreover, the relatively low common mode rejection ratio of the amplifiers of the Vitaport 1 renders the EEG and other low voltage signals susceptible to 50/60 Hertz interference and motion artifacts, especially during prolonged recordings when electrode impedance can become high over time. As a consequence, a new device was built containing extensive capacity for data storage (170 MByte), a high precision amplification system and a powerful 32 bit processor to allow for on-line and sophisticated preprocessing of incoming data. The amplitude resolution is 12 bit by default; 8 bit is possible to save disk space and 16 bit is possible using over sampling.

To allow for more flexibility concerning the number of channels needed and therefore weight and cost of the system, amplifiers and A/D converters were placed on analog modules with a capacity of 8 or 16 inputs each with different properties (depending on the module installed). Different types of modules can be flexibly combined to built a unit with up to 64 channels to meet almost any application in field research, but also for clinical physiological monitoring, e.g. in polysomnography, multichannel EEG holter monitoring, diagnosis of epilepsy, or pharmacological studies (Mutz, Martens & Stephan, 1994). Figure 2 shows the view of the recorder with the main unit and two analog parts.

The unit with one analog module has a weight of 750g (including the 4 penlight batteries) and a size of 9 x 15 x 4.5 cm. For each further analog module height increases by 1 cm and weight by 150 g. Figure 3 shows the internal structure of the recorder.

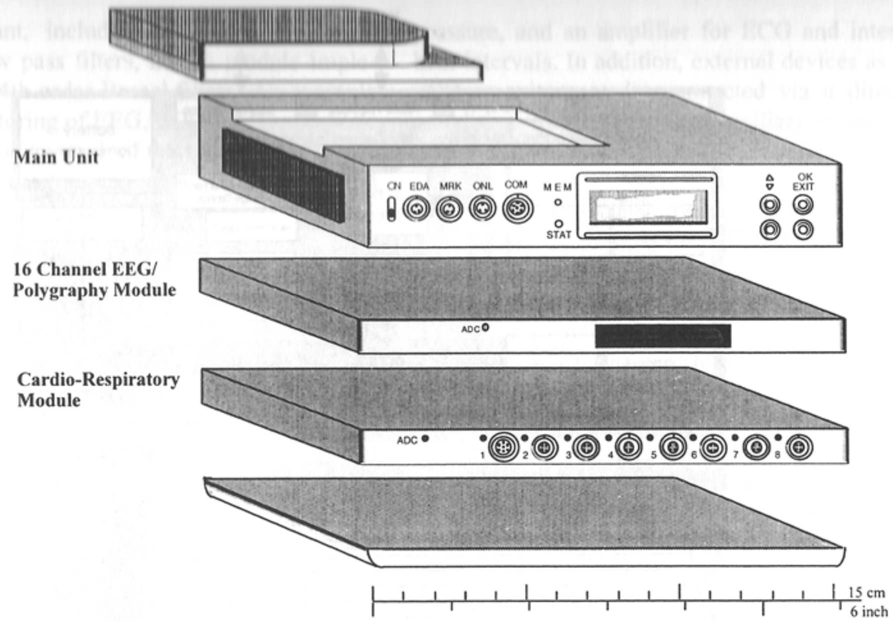

Figure 2: View of the different modules of Vitaport 2

The main unit

The main unit (see also Figure 3) contains a 32 bit fixed point microprocessor, cycling at 16 MHz. It can carry out real-time signal processing tasks such as low, high and band pass filtering, the FTFT (Fast Time Frequency Transform, see below), QRS detection, the computation of integral, area and the like. Furthermore, the processor can handle custom designed real-time SPIL programs (Signal Processing & Inferencing Language, see below) for instance to generate custom determined alarms.

The total throughput of the main unit equals 16 KHz and the maximum number of channels is 80. Exchangeable PCMCIA comprise media such as a 16 MByte RAM card or a 170 MByte hard disk. Multiple files from different recordings can be stored on one medium.

The main unit communicates via an RS232 serial bi-directional interface for both data transfer and recording control with the host computer to allow for control and supervision, either directly or via an ordinary or wireless telephone line. A special bi-directional digital interface allows for communication with other devices such as the PSION digital diary. The high speed read-out of the storage media is done via a PCMCIA card reader.

The main unit also supports the measurement of conductance (2.5 to 250 mS) for measurement of electrodermal activity or of impedance (4 to 400 KOhm) for control of electrode impedance.

The main unit consumes from 10 mA in low power 'sleep' mode with serial line disabled, to 30 mA with the serial line active, up to 120 mA, depending on scan rates and digital processing tasks.

By means of 4 push buttons and a 2 x 16 character display the main functions can be selected via simple two-line menus on the device itself. By these means, major functions like

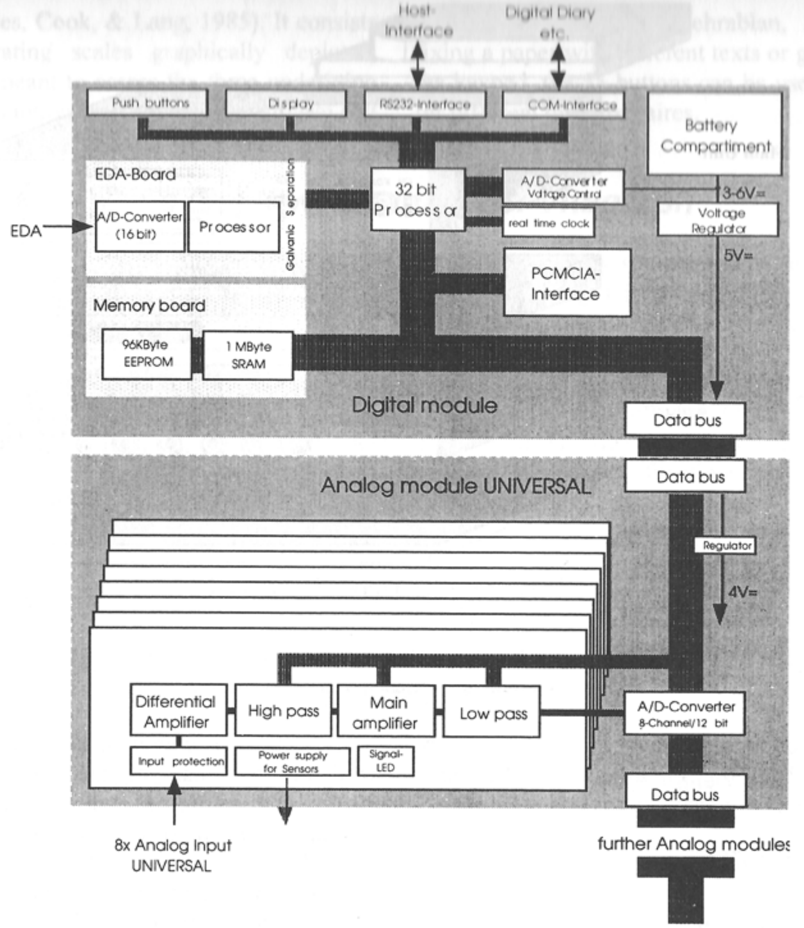

Figure 3: Block diagram of Vitaport 2

starting and stopping the recording, selection of signals to be stored, rudimentary control of signal quality, etc. are possible in the field without connection to a computer.

The analog modules

The different analog modules of Vitaport 2 can be combined according to the users' demands to built a unit with up to 64 channels (see Figure 2).

Currently, there are 3 types of analog modules to address various applications. The weight of each module is around 150 gram. A two module system with a total weight around 900 gram can comfortably be worn on the body. Such a two module device enables full high quality 24 to 32 channel polysomnographic recording in the laboratory or at home under full on-line supervision via a telephone line.

The 8 channel universal module

For research applications in general several types of variables, sensitivities, bandwidths and signal processing are requested. Therefore this 8 channel "universal" board has been designed to offering a wide programmability for each channel independently (see Table 1) concerning time-constant, including DC, gain and anti-aliasing low pass filters, in this module implemented as 4th order Bessel filters. An example is the monitoring of EEG, EOG, EMG and ECG for sleep studies, each of the variables requiring different sensitivities, time constants and bandwidths.

The cardio-respiratory module

This module offers all the functionality required to record respiratory variables, particularly suited for differential diagnosis of apnea. It contains a full oxygen saturation unit, semi-quantitative monitoring of respiratory excursions by applying magnetic coils, processing of oro-nasal airflow and the sound of snoring, a piezo-resistive accelero sensor (see "Ambulatory Posture and Movement Analysis") for the combined monitoring of body position and movements, a bridge amplifier for esophagus pressure, and an amplifier for ECG and interbeat intervals. In addition, external devices as a pCO_2 monitor can be connected via a direct coupling to one of the five auxiliary inputs if required (see Table 1 for further details).

The 16 channel EEG / polygraphy module

This module is targeted for enhanced long-term multi-channel EEG monitoring, for instance to study daytime vigilance or epilepsy or in pharmacological studies. Secondly, it can be used in combination with the cardio-respiratory module for full polysomnography with emphasis on multiple EEG leads. In contrast to the universal module, there are only two settings per amplifier for gain, time constant and anti-aliasing low pass. The total power consumption of this module was further reduced to allow for 24 hour 16-channel monitoring on 4 rechargeable batteries.

Long term unobtrusive physiological recordings: Mini-Vitaport

Vitaport 2 is a recorder for in-depth assessment of many physiological signals with high time resolution and signal quality. A certain amount of discomfort for the subjects due to size and weight of the recorder and amount of cabling is inevitable and can lead to acceptance problems for prolonged recording periods of several days. For a complementary research strategy the Mini-Vitaport was constructed to reduce reactivity effects and discomfort of the subjects. Only through long term recordings the question of day to day variability in physiology or behavior can be addressed and weekly rhythms can be studied. Reliability of results should be increased and the data gathered will be more representative of the subjects' "normal" behavior.

With its minimal size (2.0 x 4.5 x 8.5 cm) and weight (125g) this extended actometer is most suitable for long term recordings of a few important signals, e.g., over a period of one week. The data storage is done on solid state memory with a capacity of up to 1 Mbyte.

In low power mode the power consumption can be reduced to 4 - 8 mA, so that the battery (type micro/AAA) can last for one week, when recording up to 4 channels (e.g., heart rate, respiration, activity, event marker).

The first channel is suitable for recording of ECG, EEG, EMG, etc. Sensitivity is adjustable in two steps. A hardware integrator can be switched on/off by software for EMG recordings. A hardware trigger for QRS detection in the ECG can be used to store heart rate or inter beat intervals. The second channel can assess respiration, temperature, airflow or other high voltage AC signals. Electrodermal activity is recorded on another channel with 16 bit resolution (not possible in low power mode). An event marker is always built in and can be used to register important incidents. Further channels for activity, temperature or external signals are accessible on demand.

Table 1: Overview of Vitaport 2 channels in the different modules

Module	Channel	number of channels	Characteristics	Gain	High Pass	Low Pass
Main Unit	Communication 1	1	upto 570 kBaud assync port for host communication			
	Communication 2	1	4 MBaud synch serial bus for digital I/O			
	EDA	1	constant volt method 0.5 V DC or AC, galvanically isolated, 16 bit resolution			
	Event marker	1	2 digital inputs			
Universal Module	all purpose	8	differential or single ended sensor power supply can be switched on/off	20 - 25,000 in 4096 steps	DC to 0.015 sec, in 8 steps	10 to 2200 Hz, in 4000 steps; 4th order Bessel
EEG/ Polygraphy Module	Referential EEG and Bipolar Polygraphy	12 4	referential EEG over 12 - 16 channels; bipolar polygraphy (EMG, ECG, Respiration) for channel 13 - 16	+/- 100 μV or +/- 2 mV range	2 time constants (customizable)	2 cut-off frequencies (customizable); 4th order Bessel
Cardio-Respiratory Module	Respitrace(TM)	2				
	Airflow (thermistor)	1				
	O2-Saturation	1	photoplethismographic method			
	Plethismogram	1				
	ECG	1	raw ECG, heart rate or interbeat interval, hardware trigger, accuracy 10 μ sec.			
	Microphone	1	logarithmic amplification, matched band pass filter			
	Light	1				
	Body Position	1				
	Temperature	1				
	Bridge Amplifier	1	e.g. esophagus pressure			
	external	5		1		

The assessment of objective setting and behavioral variables

As already mentioned, the flexible channels of the universal module as well as some of the channels of the cardio-respiratory module make it possible to register ambient conditions and behavioral parameters. The temperature sensor can be used to show whether the subject is inside or outside a building, a microphone can be used to record the noise level or interruptions of sleep caused by noise or to analyze communicational behavior when someone is speaking. The light sensor is useful in sleep research for determining the "time in bed", that is from turning off the light in the evening till switching it on again in the morning. Also it can measure how much light there is in the bedroom in account of early sunrise in summer. In a study on cardiovascular reactivity (see "Applications") continuous records of posture, thigh EMG and an accelerometer fixed to the forearm were used to estimate metabolic demands on the cardiovascular system. When discussing the previous day with the subjects, these signals were extremely helpful to control their diary entries and to remind them of what had happened at a certain time. In sleep research, we use a position detector consisting of 3 mercury switches to differentiate between different lying positions. The frequency of position changes can be used as a very simple measure for sleep quality, similar to movements recorded by an accelerometer fixed to the leg. More detailed information about the situational context and behavior can be obtained by video recordings (see below).

The recording of self-reported emotional, behavioral and situational data

In many research projects using ambulatory monitoring, paper and pencil diaries have been replaced by electronic devices (Fahrenberg, 1994; Hank & Schwenkmezger, this volume). In current research plans, the content of diaries is often tailored to the specific research questions in contrast to the more general diaries used before. Only electronic devices can display questions in a branched structure that allows the sampling of maximally relevant information within short time periods. More sophisticated research plans take even additional advantage of the "intelligence" of the recording device or the electronic diary by interactive operation (see Johnston, this volume; Myrtek, this volume). Apart from clinical applications, most ambulatory monitoring studies have used time sampling methods for the assessment of psychological relevant variables so far. The interactive operation of electronic diaries and physiological data recorders constitutes a new type of event sampling method, where events are not defined by psychological features apparent to the subject, but by physiological responses.

For the recording of self-report data in combination with the Vitaport 2, a commercially available hand held computer, the "Psion 3a", is used. This computer measures 126 x 45 x 15 mm and weighs about 330 g. It has a 480 x 160 pixel graphic display and can be programmed in either OPL-basic or "C". The Psion computer can be connected to any host computer as well as to the physiological recording device via a serial link. The diary program developed for this purpose allows for a branching structure of the questions, so that maximum information can be obtained with minimum time. An automatic alarm signal can be programmed at fixed or random time intervals. To alter the questions, a simple text file has to be edited, containing only a few key commands. Complex interaction of the physiological signals can be analyzed and the results can be used to control the diary. There are three basic operation modes for the Psion:

1. Both devices can be used independently, with the physiological data stored in the Vitaport, and the self-report data stored in the Psion computer. In this way, entries into the diary can not only be made by the subject under study, but also by an observer. Afterwards, if needed, the coded diary entries can be converted into a continuous time series, which can be read into the Vitagraph program and can be displayed as a separate channel synchronous with the physiological data. A text may be assigned to each of the codes.
2. When both devices are connected via a serial link, the Vitaport can give a command to the Psion computer to start one of several diary programs. The results are again stored on the Psion computer and can be converted afterwards into the file containing the physiological data. In this interactive mode, the conditions for starting the diary and choosing the appropriate text file can be very complex and may involve computations with several of the physiological channels.
3. The Vitaport can use the Psion as a display only. All the text displayed is programmed into the Vitaport (Real-time SPIL, see below), which will also store all the keys pressed as answers into a separate channel. In this mode, it is easier to program complicated interactions of different physiological channels and respective text output. But the branched structure of the questions (the next question depending on the previous answer) is limited and the output is less comfortable to handle when analysis is done outside Vitagraph. Besides, the programming of the diary needs more programming skills.

More context information: Display of a video signal

The most comprehensive information about the behavior and environment of the subject under study can be obtained by videotape. Obviously, video monitoring is not possible in many applications of ambulatory monitoring. But as inter subject variability of situations during the ambulatory monitoring period can cause problems for the interpretation of data, standardized situations or tasks during the ambulatory monitoring period have been introduced in some studies (e.g., Fahrenberg, Foerster, Schneider, Müller & Myrtek, 1986; Gerin, Rosofsky, Pieper & Pickering, 1994). Under this circumstances, video monitoring might be possible at least for a part of the ambulatory assessment period and give valuable information.

The Vitagraph software is able to fully control the recording and display of the video tape via a serial link. According to requirements, it is possible that the display of physiological data follows the videotape or that the videotape follows the physiological data displayed. The video tape is synchronized by means of a time code with the physiological data. The accuracy of the synchronization is 40 msec. The time code is written on the CTL track of the videotape. This can be done during the recording or even afterwards. This opens the possibility to do the recording with any Camcorder or a normal video recorder. Only a synchronization signal has to be recorded simultaneously on tape and Vitaport at the beginning. For writing and reading the time code a VHS recorder with an additional time code board (GSE, official VHS time code) is needed. The video recording can then be displayed simultaneously with the physiological signals on a normal TV set or superimposed with the physiological data on the PC monitor (see Figure 4).

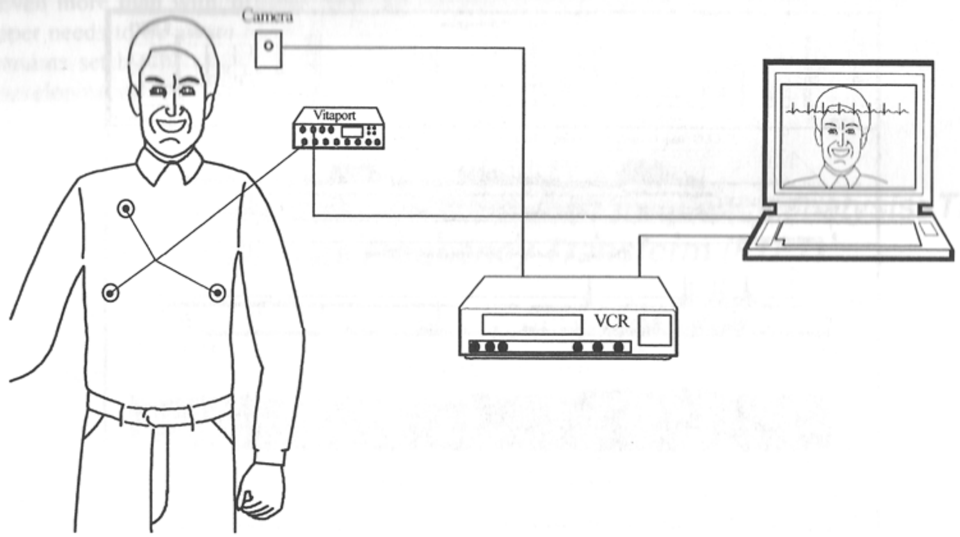

Figure 4: Display of physiological data superimposed with a video signal. With a small camera and portable video recorder this equipment can also be used in the field.

Data analysis: The Signal Processing and Inferencing Language (SPIL)

With the storage capacities of the Vitaport 2, the amount and nature of recorded physiological data exceed the capabilities of existing statistical standard software. Therefore, data reduction strategies and analysis features were included into the Vitagraph software. A special programming language was designed to be used by scientists rather than by engineers and optimized for rapid development of data reduction schemes, working upon the Vitaport data on the screen. SPIL and its modules and available programs constitute a toolbox for the researcher to develop efficiently specific solutions.

It was developed as a meta-language that handles time series as objects. This implies that the developer does not have to care about indices, sample frequencies and the like. The "Signal Processing and Inferencing Language", SPIL, allows for signal processing as filtering and transformation techniques; in addition to the well-known FFT (Fast Fourier Transform), it also includes a new and proprietary algorithm for high resolution so called instantaneous frequency analysis by means of the "Fast Time Frequency Transform" or FTFT (see further on this chapter). Besides data transformation, SPIL enables sophisticated pattern detection and data reduction by inferencing, e.g., by means of Boolean rules, fuzzy logic or template matching. Results can be saved as new time series that are added to the data set as new channels. Text/ASCII output can be stored as an input file for a statistical program or results can be printed on the screen. Graphic display of data and results of computations can also be customized and be set from a SPIL program (see Figure 5).

SPIL either operates as an interpreter or as a compiler for parts of a program. By default all operations are carried out automatically for every point of the time series. Lags in either direction can be handled very conveniently. Within a SPIL main program, it is possible to invoke nested programs and the depth of layer-

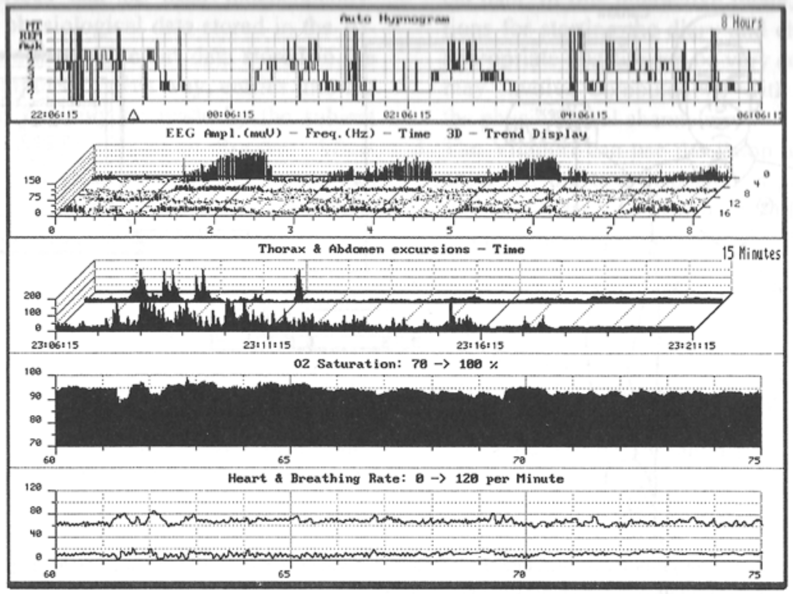

Figure 5: Typical example of a polysomnographic analysis, realized with various SPIL subprograms. The 2 top traces are on a time base of 5 hours in this example, showing the hypnogram and the detected delta, theta, alpha and spindle phasic events, using the FTFT SPIL module, in a 3-D presentation with frequency along the z-axis from 0 to 16 Hz; time resolution is 30 seconds; note the well developed delta and spindle activity in this apnea patient under CPAP treatment.
The 3 lower traces are on a time base of 15 minutes, thus revealing the medium and short term trends with a time resolution of 1 second; the envelopes of the thorax and abdomen excursions are in the 3rd window from the top, quantified using the FTFT; the oxygen saturation in the 4th window from 70 to 100 %; and the heart rate combined with the frequency of breathing (# / minutes) in the bottom window; heart rate is based on traditional QRS detection; rate of breathing is detected using the FTFT.
The little arrow in the upper window indicates the position in time of the 3 lower windows on 15 minute time base (23:06:15 in this example); apparently, the 3 lower windows were paged over a total period of 1 hour. Note the correlation between subtle desaturations and the heart rate accelerations at around 62 minutes. Also note the correspondance between the artifactial respiratory excursions from minute 61 to 67 and the hypnogram scoring 'Awake' for these epochs.

ing equals 16. Obviously, SPIL programs can operate in batch mode. SPIL takes care for the fact that channels may show different sample frequencies and definitions.

The basic structure and commands of SPIL are easy to learn and simple programs can be written within a few minutes. Examples are the marking of certain events (heart rate high, but activity low) or the combination of different channels (average of different activity channels). Whereas almost no programming skills are needed, a basic understanding of signal analysis, statistics and numerical aspects in general is mandatory to accomplish valid results.

For off-line analysis, SPIL can work with data from any of the Vitaport devices. Because of its powerful processor, Vitaport 2 is also able to perform on-line processing, that is, signal processing and inferencing tasks during the recording, written in a simplified real-time version of SPIL. First of all, it can be used to secure the quality of signals, e.g. (generically) IF INPUT > 'Max' OR < 'Min' THEN 'Alarm'. Even more than with 'off-line' SPIL the developer needs to be aware of the typical time constraints set by the real-time environment when developing such SPIL programs.

The most complex application built in SPIL so far is a package for automatic sleep stage and respiration analysis (see "In-home monitoring of sleep and automatic sleep stage and respiration analysis").

A novel approach to high resolution frequency analysis: The Fast Time Frequency Transform (FTFT)

Since the introduction of the Discrete Fourier Transform and especially the Fast Fourier Transform (FFT) some 20 years ago, spectral analysis has been applied extensively to physiological signals. Using this transformation from the time domain into the frequency domain is especially advantageous, when there are sinusoid components present within the signal. The frequency spectrum reveals sinusoid activity in the midst of noise much better in comparison to the time domain, in other words, the spectrum shows an improved signal-to-noise ratio for stationary signals.

The basic assumption for Fourier analysis however is, that the signal within the time window under study is stationary, i. e., the properties of the signal do not change over the time window.This can be true under natural circumstances such as half an hour of deep sleep for the EEG and respiration, or under artificial circumstances as a 10 seconds light stimulation paradigm during EEG investigation.

Under free-run physiological conditions, this requirement of stationarity is seldomly met, given, for instance, the randomness of stimuli from the outside world to which there is often some non-stationary physiological reaction (an acceleration of heart rate or breathing, an EEG alpha burst during micro arousal from sleep, etc.). For non-stationary phenomena, the Fourier spectrum can not be interpreted in an unambiguous manner. For a phenomenon that is present for instance only half of the duration of the time window, the amplitude in the spectrum will be divided by two compared to a stationary presence; so the initial advantage of an improved signal-to-noise ratio in the frequency domain is diminished; moreover, it is unknown where within the time window the non-stationary phenomenon was present, since Fourier transformation yields a so called time-averaged spectrum.

An obvious improvement can be accomplished by shortening of the time window over which the spectrum is calculated, the width of the time window ideally matching the duration of the phenomenon under study. The so called short-term Fourier analysis, mostly represented in illustratory waterfall displays, can overcome some of the problems related to non- stationarity. From a numerical point of view there is an accuracy problem when shortening the time window. The resolution within the spectrum is given by the reciprocal of the width of the time window. This means, that a time window of 10 seconds yields a frequency resolution of 0.1 Hertz, a time window of 1 second a frequency window of only 1 Hertz, and so forth. This poor frequency resolution for short-term Fourier spectra may be adequate for illustratory displays, but mostly it is not for quantitative objectives. For example the detection of artifacts or phasic events with a predescribed frequency spectrum (e.g., an alpha burst from, e.g., 7.5 to 11.5 Hertz) requires a time window of 10 seconds while the duration of such a burst can be less than a second. This sets an upper bound to the specificity and sensitivity of detection methods based upon Fourier analysis (Martens, Mutz & Stephan, 1993).

To overcome the limitations of poor resolution of Fourier analysis, an alternative approach was adopted, known as the "Fast Time Frequency Transform", FTFT (Martens, 1992). This method is integrated into the SPIL language. Advantages above traditional Fourier

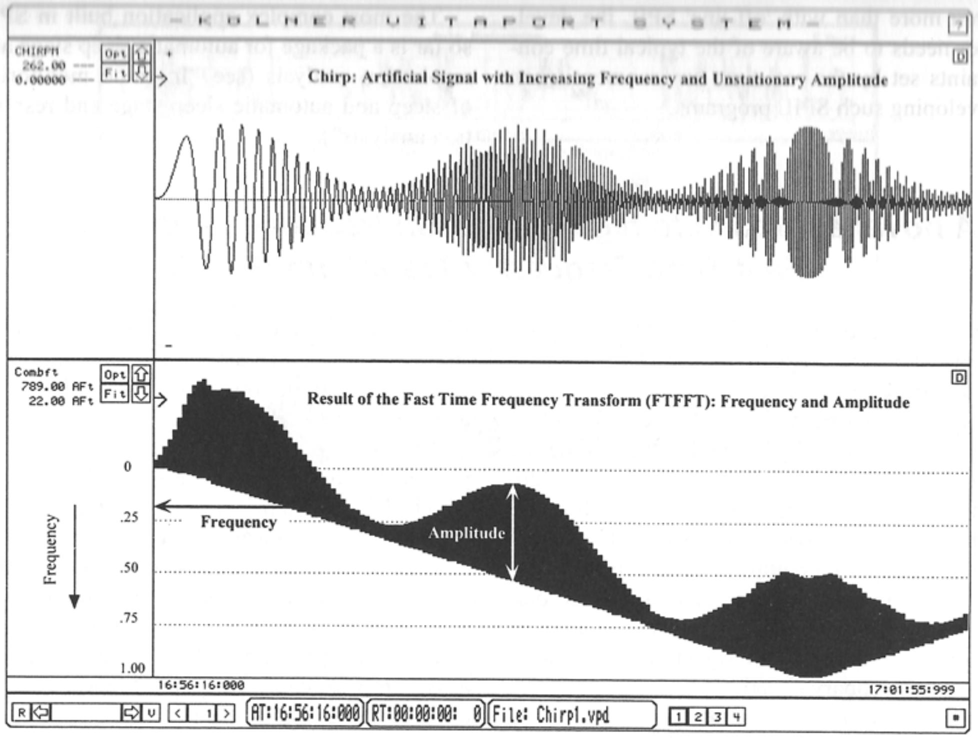

Figure 6: Illustration of the concept of instantaneous spectrum analysis using the "Fast Time Frequency Transform" (FTFT) for an artificial single component signal, a chirp, showing both frequency and amplitude modulation and sampled at an arbitrary frequency.

analysis are that the FTFT constitutes a transformation into the joint time-frequency domain, i.e. it delivers the instantaneous instead of the time-averaged spectrum. Because, mathematically, the FTFT is based on the 'analytical', so 'complex' signal rather than on the 'real' signal, frequency constitutes a continuous variable within this concept; so frequency resolution is infinitesimal and not only determined for the 1/T grid points of the discrete Fourier spectrum. Figure 6 illustrates the concept of the FTFT for an artificial 'chirp' signal showing both highly non-stationary amplitude and frequency changes over time.

The time resolution of the FTFT is given by the bandwidth of the constituting components in a given signal. In a setup procedure, the FTFT needs to be set to 1,2, 4, 8, 16 or 32 frequency bands to match the various components in a given signal. For the human EEG for instance, the FTFT is set up to comprise 8 components up to 32 Hertz, so the bandwidth of these components as delta and theta is 4 Hertz. Consequently, the instantaneous spectrum for this application is generated as much as 8 times per second (see Figure 7). Applied to respiratory signals, the effective bandwidth of the FTFT is set to 2 Hertz; so the update rate is 4 per seconds typically (see Figure 8).

Obviously, the increased resolution in both the time and frequency domains of the FTFT allows improved quantification and subsequent detection of especially non-stationary, transient wave forms (Martens, Mutz & Stephan, 1993; 1994). We make intensively use of the FTFT to detect phasic events and artifacts during long-term monitoring. Instantaneous frequency and phase on top of amplitude yield another degree of freedom not available so far for enhanced detection and classification of apneic events. We also use the FTFT to spot the instantaneous frequency of walking during movement analysis (see below). Currently, we are investigating the benefits of FTFT analysis on heart rate fluctuations; obviously, first the heart rate should be high pass filtered to remove the 'quasi-DC' component. The most important advantage of applying instantaneous frequency analysis to all these types of variable is, that, although they all may have their typical FTFT setup, in the end it is possible to study the instantaneous changes over all variables and their relationship changing over time without the disturbing 'smearing' effect of window-based Fourier analysis.

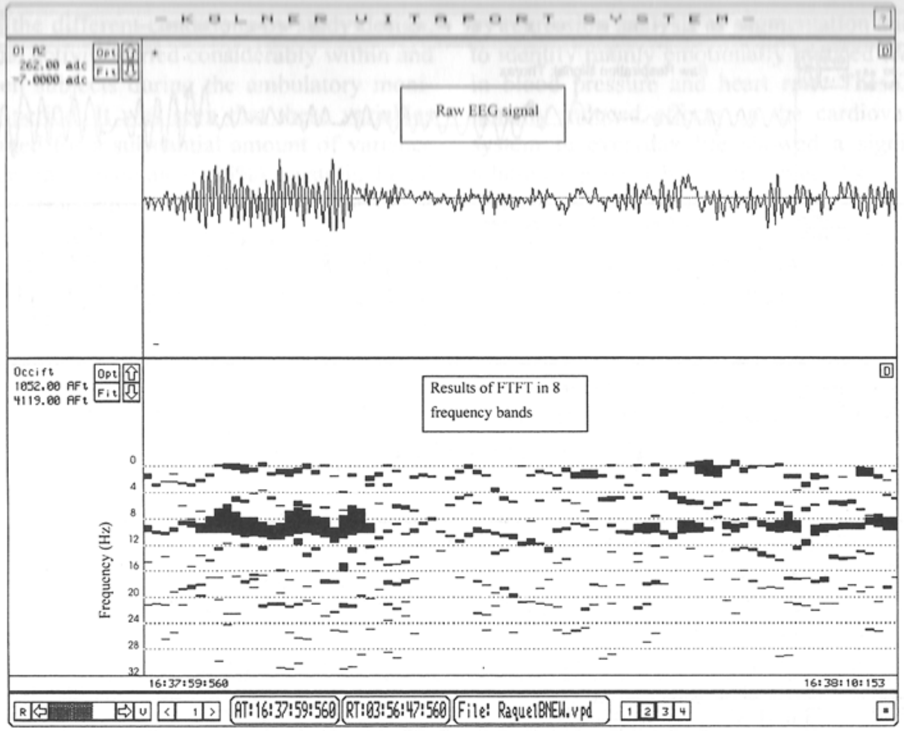

Figure 7: Illustration of the concept of instantaneous spectrum analysis using the "Fast Time Frequency Transform" (FTFT) for an 8 component signal as the human EEG, sampled at 64 Hz in the top trace. With the FTFT set to 8 frequency bands, the time resolution of the FTFT is 1 / 8 of the original sample frequency of the input EEG and corresponds to the elementary bandwidth of the components, being 4 Hertz; as a consequence, time resolution is 0.125 seconds with this setup.

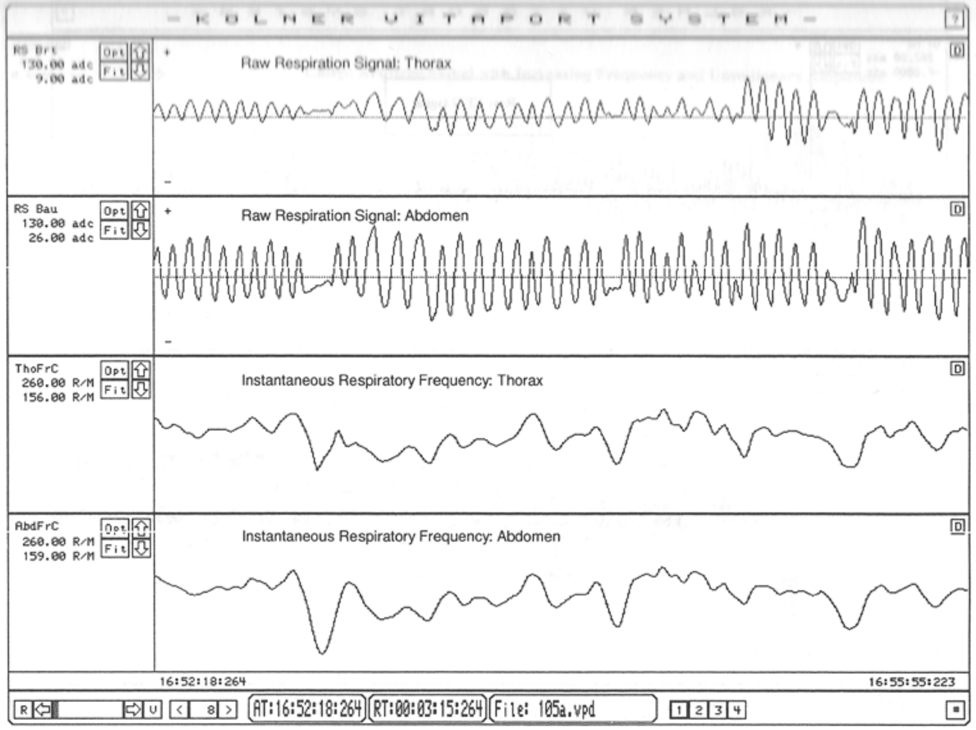

Figure 8: Illustration of the concept of instantaneous frequency analysis for 2 respiratory signals, sampled at 8 Hz for a patient under treatment at a dentist. The 2 bottom figures show instantaneous frequency as a continuous function of time for the 2 upper signals up to a rate of 26 per minute (scaled up a factor 10 here). Note the drops of frequency during a short cessation of breathing, also note the very high correspondance between the frequency traces, irrespective of the clear amplitude differences between the original signals.

Some applications

Comparing cardiovascular responses to a laboratory stressor to reactions in everyday life

Until recently most research on the effects of behavioral stressors to the cardiovascular system was based on laboratory studies. The underlying assumption, that laboratory measures are related to reactions in everyday life, has still to be tested.

To address this question, a Vitaport 1 was combined with Portapres, a device to measure blood pressure continuously and noninvasively in the finger (see Schmidt & Jain, this volume). In addition to the cardiovascular variables (heart rate, systolic blood pressure and diastolic blood pressure) thigh EMG, movement of the dominant arm and body position were assessed once per second in the laboratory and during a 24 hour ambulatory period in 18 healthy male medical students. Situational variables and mood ratings were gathered by means of a paper and pencil diary (Jain, 1995; Jain, Schmidt, Johnston, Mutz & Stephan, 1995).

In contrast to the laboratory situation, where the level of physical activity was controlled across the different conditions by study design, physical activity varied considerably within and between subjects during the ambulatory monitoring period. It was seen that these variables accounted for a substantial amount of variance in heart rate (median = 55%), systolic blood pressure (median = 15%) and diastolic blood pressure (median = 14%). The recorded activity measures (EMG, accelerometer and body position) were therefore useful to rule out effects of physical activity to the cardiovascular system by regression analysis or segmentation and thus to identify mainly emotionally induced changes in blood pressure and heart rate. These emotionally induced effects on the cardiovascular system in everyday life showed a significant relationship on a between subject basis to the active coping laboratory stressor, especially in rate pressure product and heart rate (for further details of this study, see Jain, 1995; Schmidt & Jain, this volume).

In-home monitoring of sleep and automatic sleep stage and respiration analysis

Sleep, sleeping habits and sleep quality are to a certain extend dependent on the sleeping environment. Recommendations for polysomnography in the sleep laboratory always include one adaptation night to account for the "first night effect" (e. g., Agnew, Webb & Williams, 1966; Penzel et al., 1993). Also, it was found that normal sleepers often sleep worse in a sleep laboratory than at home, while this is not true for insomniacs (Frankel, Coursey, Buchbinder & Snyder, 1976). Obviously, environmental factors such as noise, temperature or the presence of other persons, that exist in the natural environment and have an influence on sleep, can not be assessed in the laboratory. Finally, the effect of habits like caffeine or alcohol consumption or watching TV before going to sleep can only be studied at home, where these habits are embedded in the natural life context. Given the technical equipment available today, in-home monitoring of sleep might be the method of choice for many applications of polysomnography.

For in-home monitoring of sleep, we use a standard setting close to suggestions of the Mayo-clinic (Harris, 1991). To be able to record all relevant signals, we combine an 8 channel universal analog module and a cardio-respiratory module. This allows to record two channels of EOG, one EMG (submentalis) and three EEG channels (C_4-A_1, F_z-C_z and C_z-O_z). From the cardio-respiratory module, we record respiratory excursions of thorax and abdomen by means of respitrace or a silicone belt (Kemp & Duin, 1994), airflow, O_2-Saturation, ECG, pulse wave, skin temperature, leg movement, body position, snoring sound and ambient light.

To control for technical problems such as loosening of electrodes or decline in power supply, the recorder can be connected via a modem and a normal telephone line to the sleep laboratory or to the experimenter's home for online supervision.

Data analysis is realized by the most complex application built so far in SPIL, a package for automatic sleep stage and respiration analysis. The criteria and reference thresholds, that are normally used to detect certain phasic events and to define sleep stages according to the rules of Rechtschaffen and Kales (1968) are not frozen within the SPIL programs but rather kept in separate, so called Knowledge Base files. This is to allow easy update of criteria without having to modify the SPIL program, e.g., to compensate for inter individual variability of the physiological signals (Martens, Mutz & Stephan, 1994).

The SPIL program gives control over the various display options. In Figure 5 various time bases are combined within one screen. At the top, there is the sleep profile in terms of the hypnogram together with the constituting detected phasic events in the 3-D display in the second window. The fact that within this 3-D display, the various delta, theta, alpha and spindle components emerge so 'clean' is based upon the detection, using the FTFT of even the shortest burst event and upon separating them from the stationary background and from artifacts, initially on a 0.125 sec. basis. A traditional way of quantifying such traces comprises the integration of power over frequency bands of Fourier spectra, calculated over 30 seconds epochs; in such case, due to the impossibility of such method to discern phasic from stationary events, one always will find a substantial superimposed background noise, that, in the end, also contributes to a lower reliability of the hypnogram in such case.

To allow the clinician a scanning through the respiratory variables with an adequate resolution in time, the third and lower traces are on a 15 minute base and reflect medium term respiratory fluctuations with a resolution of around one second (see the legend of Figure 5 for further explanation).

Ambulatory posture and movement analysis

In applications where physiological parameters as heart rate variability, blood pressure, respiratory arrest during sleep or circadian body temperature are of interest, posture and activity monitoring constitute a means to reveal the effects of posture and movement where up to now this contribution remained an unknown and masking factor. In addition, the monitoring of postures, movements and further kinematic parameters may serve as a goal, e.g., in gait analysis in rehabilitation, in ergonomics and the studying of energetic aspects of movements, for defining tremor and mobility and activity patterns, e.g. in neurological applications.

Accelerometers of the piezo-resistive type reflect the position of body segments as well as movements (Veltink, 1993), because they do show a bandwidth from DC to several tenths of Hertz. The fact that they are very small and that they can easily be mounted to almost any spot on the human body opens a wide variety of practical applications.

Utilizing the DC components of two sensors, tangentially and radially mounted onto the thorax and on the upper leg, postures as sitting, lying and standing can be detected as explored by Veltink (1993) and Bussmann, Veltink, Martens and Stam (1994). The AC components of these sensors represent movement in a general sense.

For discrimination between postures and movements, the broad band accelero signals are low pass filtered at 0.5 Hertz using a steep filter. According to Bussmann et al. (1994), various postures can be detected with a reliability of around 95 % using 3 sensors and a 'fuzzy logic' (implemented using SPIL) classification approach.

The broad bandwidth from 0 to 50 Hertz allows various activities to be monitored (Martens, 1994). The part of the signals above 0.5 Hertz is used for general movement discrimination. For detecting cyclic movements, the spectrum is further limited to 4 and 2 Hertz for the trunk and the legs respectively using a steep filter followed by FTFT analysis, yielding the frequency of walking or bicycling. During staircase climbing or bicycling, the average position of body segments differs from walking, although these types of movements also show a cyclic behavior with possibly the same repetition frequency. So for discerning them from regular walking, one also has to take the DC components into account as well as the amount of harmonics present within the signal above 4 Hertz.

Figure 9 shows a typical example of this type of signals during a period of changing positions and of walking.

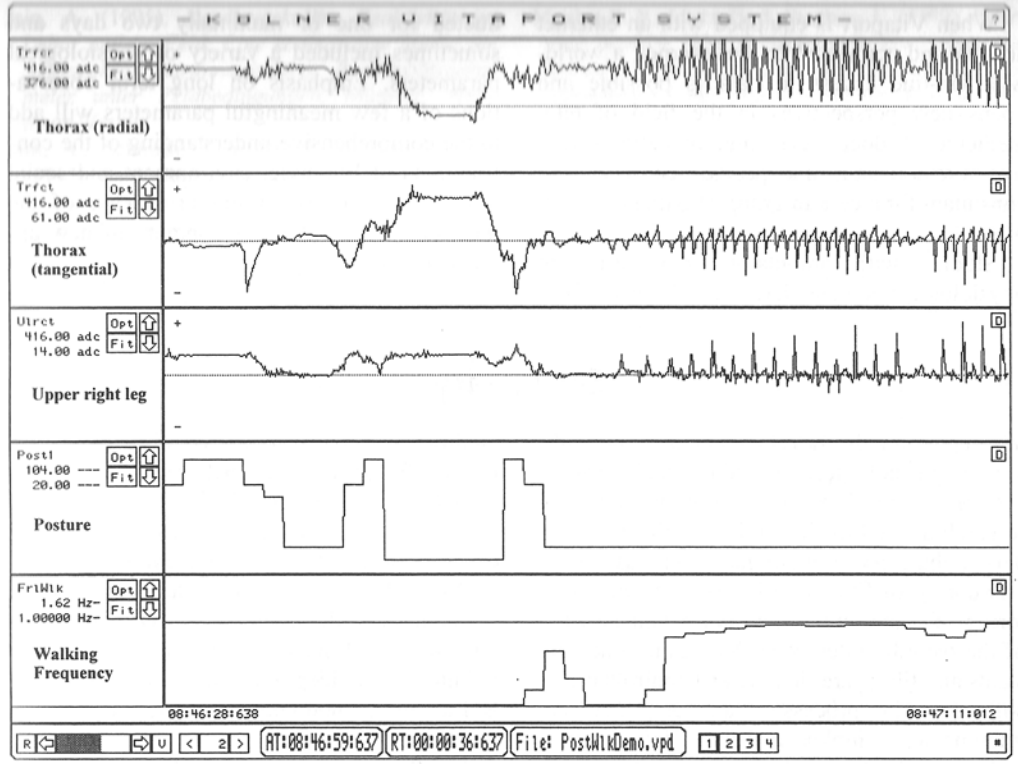

Figure 9: Accelero signals from sensors, radially and tangentially mounted onto the thorax and on the upper right leg. The signals are sampled at 32 Hz and range globally from +/- 2 g. Time base represents 32 seconds here. Note the transition from various postures as sitting, lying and standing (at the left) reflected by the DC shifts to walking (at the right). A clear heel-strike is seen in the broad-band signal from the leg (and even in the trunk signal at twice the frequency of the leg). The graph in the fourth trace represents changes of postures (in arbitrary units). The lower trace represents the frequency of walking (in this case around 1 Hz), derived from the FTFT of the bandpass filtered signals after checking against some detection rules.

Perspectives

The most prominent features of ambulatory monitoring are the assessment in the natural environment and the possibilities to record over prolonged periods of time. The information obtained in this way is valuable both for research in various fields as well as in a clinical context. Up to now, monitoring of physiological functions has been restricted to a few hours or days.

The capacity of the recorder to do on-line analysis together with advances in telecommunication opens new dimensions for long term monitoring of high risk populations. In Cologne, a project is running to monitor babies at risk for the "Sudden Infant Death Syndrome" (SIDS). The goal is to program the device in a way that it can detect critical states of the physiological system and then automatically makes a wireless connection to the hospital to transmit the data via a wireless data communication network (Modacom).

When Vitaport is equipped with an ethernet adapter and connected to the Internet, a world-wide on-line access to data is possible and opens new perspectives in the field of tele-medicine. A doctor can monitor patients who live in remote sites or a specialist can work as a consultant for a certain group of patients world-wide.

Studies with ambulatory monitoring of physiological signals have mostly been conducted for one or maximally two days and sometimes included a variety of physiological parameters. Emphasis on long term observations of a few meaningful parameters will add to the comprehensive understanding of the contributions of life style, environment and social relationships to well-being or disease of the individual and to the development of new approaches for therapy.

Summary

We report on the development of a portable, digital physiological recording and analysis system appropriate for psychophysiological research as well as for clinical applications under ambulatory conditions, such as holter monitoring of ECG or EEG or in-home monitoring of sleep and respiration. Characteristics of the recording device such as gain, time constants and filters are flexible and controllable by software. The processor can carry out programmable, complex real-time data analysis and feedback of critical states during the course of measurement.

The software comprises control of the recorder as well as sophisticated data analysis and facilities to customize presentation of results. Further features are the potential to connect a digital diary, control of and synchronization with a video recorder and full telemetric control of the recording device via a telephone line.

As applications of the system we describe research on cardiovascular reactivity under ambulatory conditions, a set up for in-home monitoring of sleep with full polysomnography and a new methodology for posture and movement analysis.

Finally, the importance of longer recording periods to obtain information regarding life context is stressed.

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