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Realtime Measurement of Stroke Volume – An Adaptive Monitoring System and Its Application*

Echtzeitbestimmung des Schlagvolumens – Ein adaptives Monitoring-System und seine Anwendung im Bereich der Kreislaufforschung

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A variety of monitoring systems is available for special fields of clinical application and scientific research. Whenever requirements change data acquisition and handling of signal analysis have to be adapted or even completely new structured, especially in real-time applications. This can be a time consuming procedure. In order to be able to focus on the development of algorithms without taking care how data are acquired a monitoring system has been developed which can be adjusted in terms of signal acquisition, analysis and user handling. New algorithms can be added and polygraphical presentation of results can be adjusted for special clinical requirements. As a specific application the online and real time calculation left ventricular ejection time (LVEJT), stroke volume (SV), cardiac output (CO), mean blood pressure and total peripheral resistance (TPRI) is presented.

Schlüsselwörter: Echtzeitanalyse, nichtinvasiv, Impedanzkardiographie, Schlagvolumen

Es gibt eine große Anzahl unterschiedlicher Monitoring-Systeme für spezifische klinische Aufgabenstellungen. Wenn sich das Anforderungsprofil ändert, müssen jedoch Signalerfassung und Analyse neu strukturiert werden. Es wurde daher ein Monitoring-System entwickelt, welches in den Bereichen Signalerfassung, Analyse und Benutzersteuerung an unterschiedliche Anforderungen angepaßt werden kann. Neue Algorithmen können problemlos integriert werden, und die polygraphische Darstellung der Ergebnisse kann den spezifischen klinischen Anforderungen angepaßt werden. Als spezielle Anwendung wird die kontinuierliche Überwachung des Kreislaufs durch die Bestimmung der Austreibungszeit des linken Ventrikels, des Schlagvolumens, des Herzzeitvolumens, des mittleren Blutdrucks und des peripheren Gefäßwiderstands vorgestellt.

1 Introduction

Based on a cerebral monitoring system, which was able to record EEG and auditory evoked potentials (BAEP) simultaneously [6], a 486-PC compatible monitoring system has been developed, which acquires EEG, somatosensory evoked potentials (SEP), BAEP and ECG continuously [12]. Additionally slowly changing physiological parameters like respiration and temperature were recorded. This system was used for monitoring of comatose patients in intensive care units [7, 4, 9, 10], for studies of sudden infant death syndrom [5] and psychophysiological studies [1].

Experience obtained during the last few years has shown the necessity of an even greater flexibility of this monitoring system:

i) It has to be adapted to changing requirements of scientific research as well as clinical applications.
ii) The medical expert however, is only interested in his specific application and in an easy handling of the system. Especially for clinical applications it is necessary to start a predefined setup of the monitoring system without any further adjustments [13].

These contradicting requirements are met by a new monitoring system. It consists of a database for administration purposes and a monitoring kernel for realtime analysis. An offline module allows detailed analysis of data recorded by the monitoring kernel and administered by the database.

2 Methods

2.1 Basic concepts

In order to combine the contradictory requests i) and ii) some basic definitions are necessary which will be used to define a hirarchy of administration levels for the user as well as for the system engineer.

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A physiological signal is treated as a time series with a specific range of values in given units. It is acquired by the computer through special devices and therefore it has to be calibrated.

Signals are analysed by functions. They require data of a specific size and type. They might be graphically presented or used by other functions as input.

An evaluation is a network of functions: It starts by analysing raw signals and ends up with the graphical presentation of results. Sample frequencies and array sizes are defined.

A configuration is a specific application realized through the combination of evaluations. For the configuration specific signals have to be recorded and results (trends, spectra) are calculated.

Measurements are taken with a special configuration. With the configuration all necessary signals and their sample frequency, default values of function parameters as well as the layout of the screen are described. Function parameters can be adjusted for the specific measurements. Data of patients are connected with configuration parameters to guarantee the reproducibility of the measurements.

Administration levels for the user

By means of the basic concepts, independent levels of growing complexity are defined for the administration part of the system. The user decides, if he is satisfied with the predefined standard configuration or if he wants to adjust parameters according to his specific requirements. Parts of the administration moduls can be protected against unqualified accessment by means of passwords. The administration levels can be described as:

1. Start of measurement with predefined configurations and default parameters of functions is possible without further adjustments.
2. Adapting function parameters for measurements. Parameters needed for functions during runtime are e. g. the frequency range of filters and spectra, or physiological characteristics of individual patients. All of them have default values given by the system engineer, which can be changed.
3. Administration of patient data is integrated in the monitoring system to allow an automatic reference between the clinical informations, recorded data and calculated results.
4. Selection among predefined configurations. Configurations are prepared for different applications. For each measurement it is possible to choose the right one for the specific task.
5. Preparation of configurations according to personal requirements. All available evaluations can be combined to a configuration by selecting at least one graphical presentation for raw signals, trends or spectra. Two screen pages can be adjusted independently in terms of value ranges and time axis.

Administration levels for the system engineer

The engineer has an additional interface for system changes.

1. Adding new signals to the measurement system. New signals are given a name. They have to be calibrated for their devices and are connected to the monitoring system.
2. Defining and changing Configurations. All functions and physiological signals added to the system can be used to predefine specific applications for the medical expert. The logical connection of functions and signals is described by means of a formal description language in ASCII-files without needing any knowledge of the monitoring concept. Syntax checks are performed by the administration modul.
3. Integration of new algorithms. Algorithms have to be written in C and linked to the monitoring kernel. An ASCII-file is passed to the administration modul to enable the design of configurations. Again, no knowledge is needed how functions are handled by the system. The administration modul is responsible for translating information given by the system engineer in terms of the monitoring kernel.

2.2 System modules

The administration part is an independent program. It translates user requirements to information for the monitoring kernel and passes them via an ASCII-file. Figure 1 shows the information passed to the modules of the kernel which are adjusted independently. The data acquisition and storage module receive information about the sample frequency of the signals and their connections to the channels of the AD-Converter.

Functions to analyse signals are interpreted by the command interpreter. The memory manager passes data and information between functions. The polygraphic layout of the screen is adjusted and used as an interpretation context for user actions during runtime.

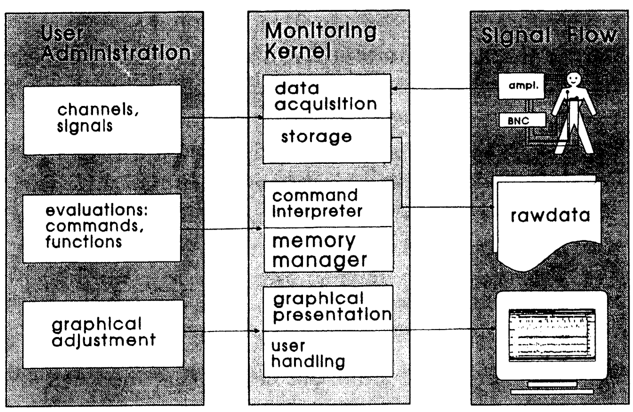

Fig. 1. Modules of the monitoring system and their connections.

2.3 Data acquisition and storage

32 physiological signals with a maximum overall sample frequency of 48 kHz can be recorded. Data are acquired through a 32 channel, 12 bit AD-converter on a IBM-PC 486 compatible computer with 33 MHz. As soon as one signal is registered in the required sample frequency and time length, calculations of evaluations related to this specific signal, are allowed to start. Consequently functions are not processed in a general chronological order.

To enable data exchange with other research institutions, signals can be stored in a standardised form [2]. Saved data are used to improve and develop algorithms.

2.4 Signal analysis

The input for a function may be a combination of results of calculations on different signals. In order to ensure their availability in time, semaphores are used to control chronological processing of data. Loops and initialising phases can be formulated to distinguish between different phases of signal processing.

This information is not handled by the functions themselves. They are embbeded in the combination of algorithms and presented to the command interpreter of the system, which is responsible for the establishment of a chronological order of the function calls.

The coordination of memory and data allocation is done by the memory manager. The total amount of memory and the number of requests on specific results during runtime is calculated. Erasure of raw signals and results, which are required for further calculation is prevented until all functions involved have finished processing. Whenever it is possible, the same memory is shared by different functions. This keeps the runtime requirement of memory to a minimum. The memory manager is called before and after each function call to allocate and free necessary memory.

2.5 User handling during runtime

Data acquisition and evaluation must not be interrupted by the user. Therefore a finite state machine was implemented. Each allowed user event is administered together with a function and a status of the machine in a table. The status symbolises the reasonable context, in which the user can take the action.

The table of feasible functions can be exchanged to adapt the system to different demands.

2.6 Task scheduling and system integrity

The tasks emerged from the monitoring modules are not processed chronologically. They are scheduled through a queue manager depending on their priority: data acquisition and storage are of greatest importance, data analysis has higher priority than graphical presentation, user dependent functions of the finite state machine are served last.

The queue manager checks the number of tasks in every queue in order to be able to detect a system overload. To prevent the breakdown of the overall system it can perform only those with higher priority.

The memory manager independently controls, whether all functions receive a specific input before it is overwritten. This is also done with the requests on raw signals passed by the data acquisition module.

2.7 Formal description language

Information about new algorithms and signal evaluations are added to the administration part of system by means of a formal description language. ASCII-files are used to describe functions and evaluations. They are read by the administration module. Information is necessary for defining configurations, changing measurement parameters and generating the transmission file for the monitoring kernel.

Definition of functions: Each function has an identification number and a name. The number and types of all required input parameters are defined. An edit mode indicates if the user is allowed to change parameters of a function or if this can only be done by the engineer. Additionally, information is provided whether the function may be used to process raw signals without any preprocessing. Figure 2 shows an example for a function definition.

```
# Function Id
  8
# Function Label
  FILTER

# Function Text
 "Digital filtering of input data"

# Nr of IArrays,  OArrays,  Parameter
  1               0         3
#-----------------------------------------------
# Inputarray Text               Type    Preprocessing
 "Input Data, double sized!"    SHORT   NO
#-----------------------------------------------------
# Parameter Text                Type    Edit
 "Upper frequency/Hz"           FLOAT   YES
#-----------------------------------------------------
# Parameter Text                Type    Edit
 "Lower frequency/Hz"           FLOAT   YES
#-----------------------------------------------------
# Parameter Text                Type    Edit
 "Sample frequency/Hz"          FLOAT   NO
#-----------------------------------------------------
```

Fig. 2. Example for a function definition: The filter overwrites the input array with his result. Cutoff frequencies may be adjusted by the user. The sample frequency however, must not be changed.

Definition of evaluations: Evaluations are functions connected to special signals and among each other. They are formulated independently, and may use all functions known by the monitoring system. Default

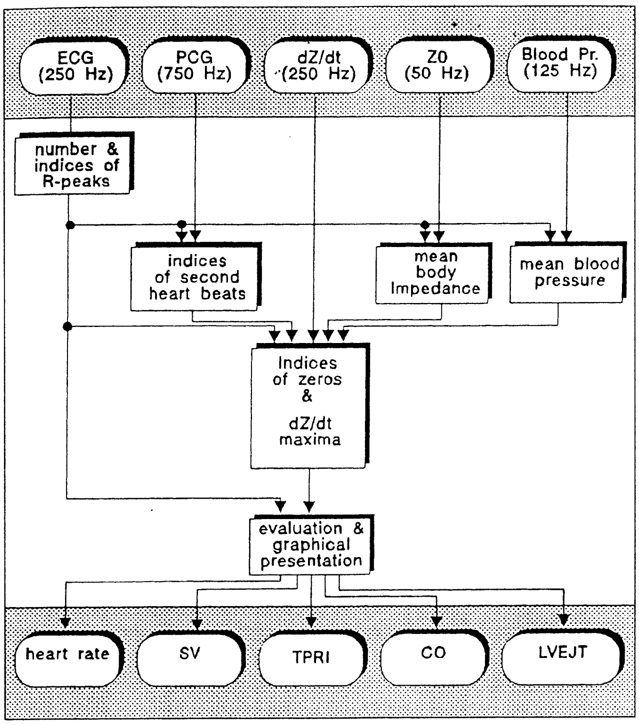

Fig. 3. Signal and functions necessary to evaluate cardiovascular parameters based on the formula of Kubicek.

parameters for every function are formulated. Signals are connected to each evaluation. Their sample frequency and average time is fixed in order to define all array sizes.

Control structures for the command interpreter are defined separately at the end of an evaluation definition.

3 Results

A non-invasive method to measure cardiovascular parameters has been applied by means of the described

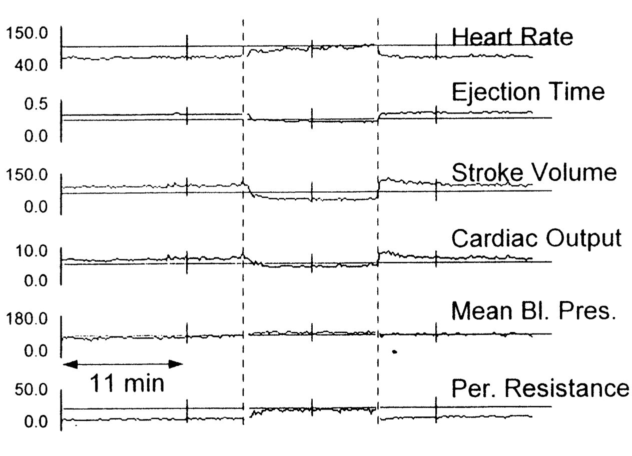

Fig. 4. Example for 36 minutes of orthostatic test with tilting table. After 15 min rests the proband was tilted 60° upright (first dotted line). After another 10 minutes he was tilted -10° head down (second dotted line). The standing position leads to a decrease of strokevolume. This effect is compensated with an increase of heart rate and a decrease of ejection time. All changes are reversed completely by the subsequent head down tilt.

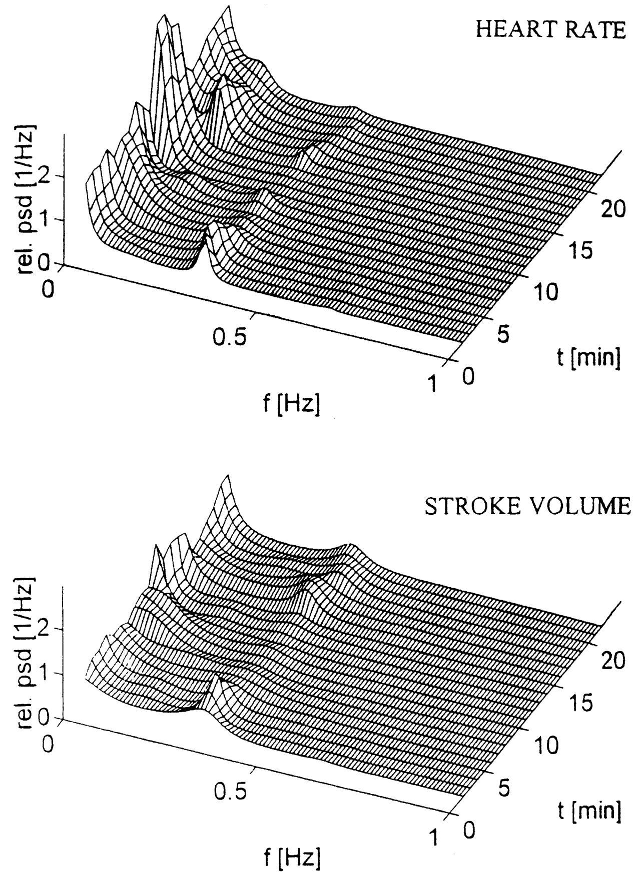

Fig. 5. Spectral analysis of heart rate and stroke volume during 22 minutes, including the change of body position after 13 minutes. Spectra are calculated using autoregressive models of order 7 fitted to segments of 4 minutes duration. The segments are shifted by one minute. Spectra are normalized by dividing through the total power. The enhanced power close to 0.3 Hz is due to the respiratory sinus arrythmia.

monitoring system. Electrocardiogram (sampled with 250 Hz), phonocardiogram (750 Hz), impedance cardiogram (250 Hz) and pulse pressure (50 Hz) are recorded and used to calculate left ventricular ejection time (LVEJT), stroke volume (SV), cardiac output (CO), total peripheral resistance (TPRI), based on the formula of Kubicek [3]. Figure 3 shows the connection of signals and functions, which are necessary to calculate SV. Results are presented on two screens. The first shows raw signals and beat-to-beat values of stroke volume and TPRI. The other presents trends of heart rate, SV, CO, LVEJT, mean blood pressure and TPRI of variable time length (from 15 minutes up to 8 hours).

Figure 4 shows that during the on-line evaluation of orthostasis, it has been possible to document physiological changes continuously. Spectral analysis of RR-intervals and SV were used to prove the physiological background of the beat to beat variations. Figure 5 compares these spectra.

4 Discussion

The implementation of the measurement system for cardiovascular parameters demonstrates the functionality of the presented monitoring modules. Although autonomic offline monitoring of SV by impedance cardiography has been performed either by signal averaging [8] or beat to beat analysis [11], to our knowledge the presented system offers the first realtime system for the simultanuous recording of SV, blood pressure and TPRI. As can be seen from the power spectra (Figure 5) the variations of SV during a stationary phase of orthostasis reflect a true physiological variation, since very similar spectra of HR and SV are obtained. This is the more noteworthy, if one considers the comparativly complex analysis of SV according to the formula of Kubicek.

There should be a great number of clinical applications of this system in cardiovascular physiology, pathophysiology and pharmacology.

Due to the modularity of the monitoring system and its formal description language, further scientific research can be focused on specific tasks without taking care of data acquisition, timing and graphical representations. It is no problem to add further algorithms, e. g. to maintain systolic and diastolic blood pressure, or to record other signals, as for example respiration.

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