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Software and Operational Concept for EIT-Based regional lung Function monitoring

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Abstract

Electrical Impedance Tomography (EIT) is a non-invasive imaging technique suitable for medical application. Most of the previous investigations have been done under laboratory conditions and only few projects under real hospital environment. This paper presents a novel concept of EIT application for clinical lung ventilation monitoring. A virtual EIT lung ventilation monitor suitable for application in clinical environment was designed and successfully implemented into the Goe-MF II EIT device developed in our lab.
The software together with its operational concept is described here. The problems of device handling, extraction of physiological relevant information from measurements, and data storage and retrieval are addressed. During data acquisition, comprehensive status information is displayed: the contact of all electrodes to the patient's body, the correctness of the wiring of the electrodes, and properties of electric or magnetic fields that produce noise at electrodes or cables.
To give a quick overview about the patients' lung function, dynamic functional images are introduced for the first time with the essential property that their screen display only changes if the patient's physiological status changes, but not during the breathing steady state condition. Additional evaluation procedures are available for series of EIT images to generate functional images in offline evaluation mode. Four different display windows are available: lung ventilation, shift-in-lung-volume, filling capacity, and pressure-volume relation. The described features of the virtual EIT ventilation monitor will be helpful to optimize the respirator's parameters for each individual patient.

Keywords

electrical impedance tomography, EIT, ventilation monitoring

1 Introduction

Electrical Impedance Tomography (EIT) is a non-invasive imaging technique used for medical application as well as for non-destructive inspection of technical devices or processes. EIT was first introduced for medical imaging in the mid-1980s by Barber and Brown [0].
For EIT imaging, electrodes are placed equidistant around a cylindrical-like object such as a human thorax. Between any two adjacent electrode pairs, a constant electric current is injected into the body under inspection while all other electrodes measure pair wise the resulting voltages at their location. By having repeated current injections and voltage measurements between all electrode pairs, a data set is established for reconstructing the body's internal structure by a mathematical operation called filtered back-projection [0]. During the last two decades, several prototypes have demonstrated the feasibility of this tomographic method [0], [0], [0], [0], [0].
Most of the previous work on EIT for monitoring and measuring regional lung functions was conducted under experimental or laboratory conditions [0], [0]. Some of the work was even carried out under extreme

environmental conditions such as micro gravity; e.g. on board the MIR space station [0], [0] as well as in airplanes on parabolic earth flights [0], [0].
To our knowledge, EIT applications under real clinical conditions are rare and have not been performed systematically. The reliable interpretation of EIT images depends on the quality of the raw data, which are frequently disturbed by higher noise levels encountered in the hospital environment. Furthermore, there is a reluctance to attach another scientific instrument to the patient with increased discomfort and interference with medical treatment.

1.1 EIT for Lung Function Monitoring

In the case of lung function EIT offers the possibility of long-term measurement and visualization of pulmonary relevant parameters. These are represented by passive electrical properties, i.e. the transimpedance of the lung tissue. Monitoring can be performed only by means of EIT since X-ray computed tomography (CT) is not applicable at the bedside and results in an excessive radiation exposure with frequent use. EIT instead delivers information about regional lung function, e.g. local ventilation and end-expiratory lung-volume for arbitrary time intervals directly at the patient's bed without radiation exposure and at very low costs [0].

1.1 State of the Art and Definition of the Problem

Usual medical equipment in intensive care unit (ICU) such as heart rate monitors are much easier to handle than existing EIT systems, since the former are easy to apply and operate automatically. Presently, a number of individual manual steps are necessary for EIT operation. These steps are: device initialization, data collection, data storage, image reconstruction, and extraction of physiological information from image series. For these steps, several software modules from different sources are usually involved. Problems arise especially in device handling, information extraction and data comparability and interchangeability. Here, the state-of-the-art is: 1.) Device handling: Time-consuming trouble-shooting is reported [0] when measured data are inconsistent. The reasons for faulty data are loose contact between adhesive electrodes and the patient's body, electromagnetic interferences and electro-static noise in the clinical environment. Static and dynamic noise is not apparent in a laboratory environment, which is electrically quieter [0], [0]. 2.) Extraction of physiological information: physiological relevant information about the patient can be extracted only off-line after some lengthy evaluation steps. 3.) Data comparability and interchangeability: in contrast to standard diagnosis methods such as X-raying no established procedures for data acquisition, evaluation and documentation exist in EIT. This means that measurement data acquired by different EIT systems cannot be compared other on a regular basis.
The described problems are the main limiting factors for clinical acceptance of EIT, especially because of the fact that clinical personnel lack engineering or EIT background. Therefore, clinicians decline to use EIT as a common tool.
It was our goal to develop an EIT-based ventilation monitor, which can be used by clinicians for monitoring the regional pulmonary function without requiring any expert knowledge on EIT or computer handling. The realization is based on the Goe-MF II EIT system [0], [0] which was built in our lab. In this paper, the software, together with its operational concept in conjunction with Goe-MF II's hardware, is described as follows: the hardware setup of Goe-MF II EIT system, the operational concept, the software implementation of ventilation monitor and the software optimization used to meet the real-time requirements will be explained in section II. In the results section, the online data processing as well as resulting PC screen is presented in the subsection A. In the subsections B and C data sophisticated data evaluation procedures available offline are described in detail. A novel solution for the monitoring regional lung function is introduced in the subsection D. And finally, the item of data interchangeability of data collected by different EIT group is addressed in the subsection E, followed by discussion and conclusion.

2 Materials and Methods

2.1 Hardware Setup

The Goe-MF II EIT device [0] comprises the core system consisting of input and output multiplexers, AC amplifier, a programmable current source, analog-to-digital and digital-to-analog converters as well as a digital signal processor (DSP), a set of 16 electrodes used as current injection and measurement probes and a host PC with graphic processor. The hardware setup is depicted in Fig. 1. The most important component in this circuitry is the high-precision low-noise amplifier, together with its constant-current source. The latter provides a current of programmable frequency and amplitude for injection into the body under investigation by means of a pair of injection electrodes. The amplifier senses the resulting voltages at each other pair of measurement electrodes.

Additional to the collection of skin surface voltages, the auxiliary analog input of the Goe-MF II device can be used to acquire airway pressure values of mechanically ventilated patients. These pressure values are accessible at the "y-piece" of the respirator. The analog input can also be used for acquiring other physiological information, if necessary.
Analog-to-digital converters and first-in-first-out buffers provide for appropriate digital access to the measurement values during data acquisition. The DSP is responsible for data preprocessing. Additional utilities such as Random Access Memory (RAM) and Direct Memory Access Controller (DMA) allow for efficient operation of the digital part of Goe-MF II. Subsequent image reconstruction and data presentation is performed by the host PC running the Windows XP™ operating system. The performance of the Goe-MF II system is described in previous publications of our group [0], [0].

2.2 Operational Concept and Software Implementation of Ventilation Monitor

The first step in the sequence of operations is the analog-to-digital conversion of the probe signals and the calculation of a so-called characteristic signal amplitude out of 1024 primary data AD-samples of 14 bits each. As a result, a single 32-bit integer is obtained as characteristic amplitude of the fundamental oscillation in the signal spectrum. Signal sampling and spectral analysis is repeated for all 16*13=208 combinations of 13 active measurement electrode pairs out of a set of 16, thereby forming a raw input data set. This is performed by the DSP. In the second step, data are transferred to the host PC via a bi-directional Universal Serial Bus link (USB) at 12 Mbits/s. In the third step, a filtered back projection algorithm is executed on the PC for image reconstruction generating 32x32 pixel image. The fourth and last step in the sequence of operations is the user's screen generation according to the above-described calculations. This comprises the interpolation of a 32*32 double-precision number matrix and the conversion of this matrix to 8 bit integer values to yield a 128*128 pixel matrix for rendering on the PC's display. Pixel interpolation was used for better visual perception by resolution enhancement. Steps 1-4 are repeated with a rate of 13, 25 or 44 Hz to get a series of single EIT images, which are required for the monitoring of regional lung function. Subsequently more sophisticated data evaluation can be started either for the last acquired (by default) or for any arbitrary data set.
The DSP´s software was written in C, tested, compiled and downloaded by means of the Texas Instruments™ Integrated Development Environment (IDE). The overall software project engineering, the generating of the graphical user interface (GUI) and the visualization was implemented under MATLAB numeric computing environment. MATLAB is commercial software, optimized for numerical calculations with matrices [see http://www.mathworks.de]. The used MATLAB Application Programming Interface (API) makes it possible to compile custom C code as a so-called MATLAB™ executable dynamic link library (MEX-DLL) and to link it to the MATLAB framework. The most time-consuming calculations such as image reconstruction, image interpolation, user' screen generation, as well as calculation of the "functional EIT images" and "dynamic functional EIT images", described later in the paper, were implemented in this way. The graphical output of MATLAB is coded in the OpenGL language, which in turn is interpreted in real time by a hardware renderer, located on the PC's graphic controller board.

2.3 Software Optimization

To meet the real-time requirements Goe-MF-II's software had to be highly optimized. To monitor reliably e.g. the ventilation distribution, the series of single EIT images for the duration of at least one breathing cycle should be used for the calculation of some derived functional parameters. Assuming breathing cycle duration of 4 s, a data set of 20 Mbytes will be collected for 13 Hz data acquisition rate for instance, thus resulting in an input stream of 5.5 Mbytes/sec. For real time visualization, these data have to be processed into a video output stream of 208 Kbytes/sec (8bits 128x128 pixel image every 1/13 sec). To achieve this, manual and automatic code optimizations had to be made. The first optimization level was obtained by using the Texas Instruments™ optimizer tool for digital signal processors. The second level of optimization was to share all computational tasks between three processors: DSP, host PC and graphic controller. They operate in a pipeline on each data set in a block wise manner. The third optimization was the replacement of array indexing by pointer arithmetic according to the following C-code example: for {i=0;i<n;i++} {a[i] =b[i] +c[i]} by a++ := b++ + c++. This avoids index checking to lie between array boundaries, thus giving more speed.

3 Results

3.1 Data Acquisition

Goe-MF II provides comprehensive information by means of two main operation modes: online data acquisition and offline evaluation. To maintain the functional integrity of Goe-MF II before and during measurements

automatically, a status determination is performed. The following status information is displayed: 1) the contact of all electrodes to the patient's body, 2) the correctness of the wiring of the electrodes (no permuted cables etc.), and 3) the presence or absence of electric or magnetic fields or waves that would produce static or dynamic noise at electrodes or cables. The first two items are continuously checked and displayed during data acquisition while the third information is only available in the initialization phase before EIT measurements start.
During the initialization phase of Goe-MF II, the sampled primary values, affected by electromagnetic noise, are visualized in the time domain as well as in the frequency domain by their Fourier spectrum (Fig. 2). Additionally to displaying this information, the electrical noise status is automatically documented in a file, allowing a remote troubleshooting by EIT experts, also in retrospective.
A block diagram of online data processing of the Goe-MF II software is shown in Fig. 3, the corresponding PC screen captured during data acquisition is shown in Fig. 4. The continuous check of the electrode contact during data acquisition is made by measuring the injected current and the resulting potential differences over the driving electrodes. The quotient of both yields the electrode impedance. A check of all 16 active electrodes pairs' impedances is carried out continuously and simultaneously with the data acquisition and the results are displayed (subview 1 in Fig. 3 and 4). Additionally, all sampled raw values of the 208 measuring electrode pairs are concatenated to build a continuous curve and presented to the user. A typical U-distribution as in subview 2 of Fig. 4 can be seen if the wiring of the electrodes is correct and if no other major disturbances are present.
In the beginning of each EIT measurement campaign, several voltage measurement cycles of the electrodes of the patient's skin surface are performed and used subsequently as a baseline reference data set (Fig. 3) that is required for image reconstruction. (The reference sets can be based either on tidal breathing in case of spontaneously breathing patients, or on controlled ventilatory conditions that are defined by the mechanical ventilator.)
Subsequently EIT data acquisition can be started. The baseline reference data and the actual measuring data are processed as $(v-v_{ref})/v_{ref}$, which serves as image reconstruction input. Then, a modified version of a filtered back-projection algorithm is used to produce individual EIT images [0]. The result of the tomographic reconstruction is the spatial distribution of relative impedance changes in the thoracic cross-section.
By using its results two essential images are computed and displayed continuously in real time by Goe-MF II's software: an EIT movie, that is directly generated out of a series of reconstructed tomographies and a so-called dynamic functional EIT image (df-EIT image), that is derived from a series of subsequent EIT images. Examples for both imaging modes of lung ventilation are shown in subview 3 and 4 of Fig. 3 and 4, respectively, and will be explained later.

3.2 Offline Mode

All data acquired in the online mode can be post-processed offline, to distill physiological relevant data out of a huge amount of measurement values. The individual images are reconstructed as described above, with a single difference: the data from any meaningful physiological condition can be freely used as the reference data set. Additional evaluation procedures are applied to the series of reconstructed EIT images to calculate other parameters that characterize the regional lung function and to generate so-called functional images. Examples of a patients' physiological status are shown in views 1-4 of Fig. 5, these evaluation modes were termed by us <u>lung ventilation</u>, <u>shift in lung volume</u>, <u>filling capacity</u> and <u>pressure-volume relation</u>.

C. Functional Images and Evaluation Views
Functional images means that a whole series of images are condensed into a single picture representing a specific regional physiological function, derived from the electrical properties of the studied body itself. To achieve a functional image, it is required to track the physiological information for every reconstructed pixel over a period of time. This tracking procedure is called the time course of the pixel. Then, mathematical parameters related to the physiological function are extracted from the time course and displayed as condensed information at the pixel's position. Since this is performed on all pixels' time courses, a series of tomograms will be reduced to a single synthetic image representing a physiological function in a concise way, e.g. lung ventilation or blood flow distribution in the studied cross-section of the body. The advantage of functional images is that they can be interpreted more easily than the original data since only medically relevant information is given.
In the functional images, derived parameters have their own scales and values different from each other and from the original data, although the same gray or color representation is used on the PC's screen. Three types of functional images are derived by Goe-MF II's software, i.e. <u>lung ventilation</u>, <u>shift in lung volume</u>, and <u>filling capacity</u>. Each functional EIT image will be abbreviated as f-EIT, in the following.

1. *Lung Ventilation*. The generation of the f-EIT image for lung ventilation is described in [0], [0]. Briefly, this technique utilizes the information in the time courses of impedance changes and computes the variation of the local impedance changes for every pixel position as functional parameter. High impedance changes within a thoracic plane physiologically are related to ventilation.

2. *Shift in Lung Volume*. The shift in lung volume image computes the mean value instead of the variation of 1.) leading to images representing long-term changes in regional air content of the lungs.
3. *Filling Capacity*. The f-EIT image for the filling capacity is based on the regional relative impedance change as a function of the overall impedance change within the thoracic plane. It images the ratio of local to global ventilation, which has been introduced in [0] as "local filling capacity".

The functional images are incorporated into four different views shown in Fig. 5, which can be displayed alternatively on the screen. The basic idea of the display concept was to show simultaneously one functional image together with xy-plots of local and global information from the series of single EIT images or from auxiliary analog input. "Local" denotes information at a given pixel position as function over time and “global” means data averaged over all pixels of a given image. The pixel position from which local information has to be displayed is selected by moving the mouse pointer to the desired position. Every local xy-plot is automatically kept up-to-date on the screen when cursor position changes, i.e. with each mouse movement. Normally, the global relative impedance time course ΔZ is displayed by averaging of all pixels of each subsequent individual image. The described operations and the resulting screen captures are shown in Fig. 5 as a block diagram.

In view 1 of Fig. 5, the lung ventilation image is shown together with the local and global time courses of relative impedance changes. The standard deviation computed here for the f-EIT is an indicator for perfusion and ventilation in the cross section of the patient's body [0]. In the second view, the shift in lung volume image is combined with the same local and global time courses as before. This view quantifies the changes in regional lung volume in a transversal cross-section of the chest, resulting e.g. from modified mechanical respirator settings with respect to a reference air volume [0] or from gravity induced shift in lung volume during posture or gravity changes [0], [0]. In the third view, the filling capacity image is shown together with a xy-plot that exhibits regional versus global relative impedance changes. This information can give insight into the local lung filling and emptying behavior [0], [0]. In the fourth view, the lung ventilation image is visualized with the regional and the global pressure-volume relations of the lung. This is considered to be useful for adjusting the respirator settings during mechanical ventilation to optimize lung recruitment and to avoid lung over-distention [0].

3.3 Dynamic Functional Imaging

EIT is the only possibility for imaging of lung function at the bedside. The most important diagnostic parameter for proper therapy planning is a monitoring of the regional ventilation distribution. The EIT monitoring solution mostly considered at present is the EIT movie consisting of subsequent individual EIT images. The information about regional ventilation distribution is contained in the EIT movie although not directly but in form of highly time-resolved local lung volume changes. Therefore, the EIT movie is not optimal for monitoring due to the continuously changing image during each breathing cycle.

A novel approach developed by the authors is an extension of the offline f-EIT lung ventilation imaging described above to a monitoring method. This technique called "dynamic functional EIT (df-EIT)" is accomplished online by recalculating and plotting a new f-EIT image immediately after a new measurement frame has been sampled. Details of this technique as well as volunteer's and clinical examples are described in [0]. Briefly, df-EIT imaging is achieved by considering lung ventilation f-EIT images only for a certain period of time by using the concept of time window. The time window has to move from frame to frame, as depicted in Fig. 6 to incorporate new frames in real time. Within the moving window, the variation for all pixels is calculated, exhibiting a conventional lung ventilation f-EIT image. Each image is scaled automatically providing the maximal color dynamic range; the color bar on the image's right side supplies the quantitative information about the instantaneous physiological impedance variation in the studied cross-section as depicted in Fig. 4, sub-view 4. Evidently, for a stationary physiological process the df-EIT image does not alter as long as the moving window length matches or exceeds the process' periodicity. The length of the window is variable and can be chosen during set-up of the ventilation monitor software.

The effect of df-EIT can be seen in Fig. 7a and 7b. Fig. 7a shows the global relative impedance change ΔZ for a healthy volunteer performing an end-expiratory breath-hold maneuver followed by spontaneous breathing. For the time period depicted by two solid vertical lines in Fig. 7a a series of the df-EIT images, which has been generated online, is plotted in a 4x4 arrangement in Fig. 7b. As expected, both physiological steady states, cardiac-related variation during respiratory apnoa (images 1-6) and tidal breathing (images 9-16), show stable df-EIT images. The display only alters during transition from apnoe to ventilation indicating the change in the physiological state.

3.4 Data Interchangeability

Data interchangeability is mandatory for the comparability of measurements conducted by different EIT groups or devices. In Goe-MF-II, a configuration setup called template is created for every clinical problem under investigation. Each template is stored in a file with a mnemonic name that allows subsequent retrieval. Consecutive measurements that may be necessary for diagnosis or therapy of a patient can be run without any delay or new manual set-up if a template file already exists. The template has to be loaded, and the measurement can begin instantaneously. Furthermore, predefined templates for EIT settings provide also external compatibility of data, if the same template is used in different locations. A template file contains fixed parameters such as the duration of the reference frame, the rate of the measurement frames (13 Hz, 25 Hz, 44 Hz), the duration of a series of measurement frames (e.g. 1min), the length of the used time window for df-EIT (e.g. 5 seconds), and several other parameters.

Additionally, a unique identification label for each patient file is provided by means of two IDs i.e. text strings, one for the hospital and one for the patient, to allow for unambiguous data retrieval. The text strings are entered manually in the set-up menu for each patient, together with the patient's weight and height and his main pulmonary diagnosis. These data are stored in an additional file type called patient file. The patients and data file names are generated automatically out of center and patient IDs to standardize data management and to avoid errors. All patient files are kept in selectable subdirectories while their IDs serve as access keys.

4 Discussion and Conclusion

In the past few years fascinating new achievements and marked improvements were reached in the technical development of electrical impedance tomography systems [0], [0], [0], [0] allowing, e.g. brain imaging or generation of three-dimensional tomograms. However, the majority of the new devices has not been applied in clinical environment and was used only under experimental conditions. The main remaining limiting factors are the EIT device handling, the need of time-consuming data evaluation and measurement disturbances resulting in low clinical acceptance of the EIT. Therefore, it was our goal to develop a novel EIT-based ventilation monitor that would fulfill the criteria for successful clinical application, both with respect to a simple and mostly automated handling as well as an immediate feedback to the clinical intervention in online mode and a comprehensive evaluation procedure offline.

The novel operational concept provides online monitoring of physiological data such as regional and global lung functions and cardiac action. The handling was optimized for a clinical setting by an intuitive graphical user interface (GUI) and continuous integrity checks. All features are accessed and controlled by the GUI; from a main menu, the user is guided by forms and pushbuttons. By this, it can be guaranteed that the measurements will be carried out under reasonable system settings, and nothing will be missed for subsequent data evaluation. Potential malfunctions will be displayed immediately during the data acquisition. The typical problem of inadequate electrode contact to the patient is encountered especially on the ICU. In the past, finding the faulty electrodes was time-consuming and tedious. By using the new software clinical personnel can avoid this problem easily.

Ventilation monitor is especially useful for medical personnel in ICUs to get a quick overview about the lung function of a patient under artificial ventilation. It provides the overview in real time, which means that a change in patient's lung function by changing the set up of the mechanical respirator is immediately detectable. By this fast feedback, it is possible for the first time for clinic personnel to set up optimally the respirator function for each patient individually. This feature is based on the novel concept of dynamic functional imaging (df-EIT) that is derived from standard functional imaging. A df-EIT image changes only when the patient's physiological status changes, but not during the ordinary breathing sequence as it is the case in standard EIT movies. By df-EIT regional lung ventilation can be monitored continuously in a similar way as heart rate or blood pressure. Additionally, more detailed and sophisticated data extraction and evaluation procedures are also available offline. The modular software structure allows easy implementation of new functional images and evaluation views.

To check the clinical potential of our EIT-based ventilation monitor application studies on patients are being carried out currently. The ventilation monitor will provide a standardized platform for clinical EIT research groups for easy exchange and comparison of data. It has to be proven during the next few years whether EIT can become established as a routine tool for ICU.

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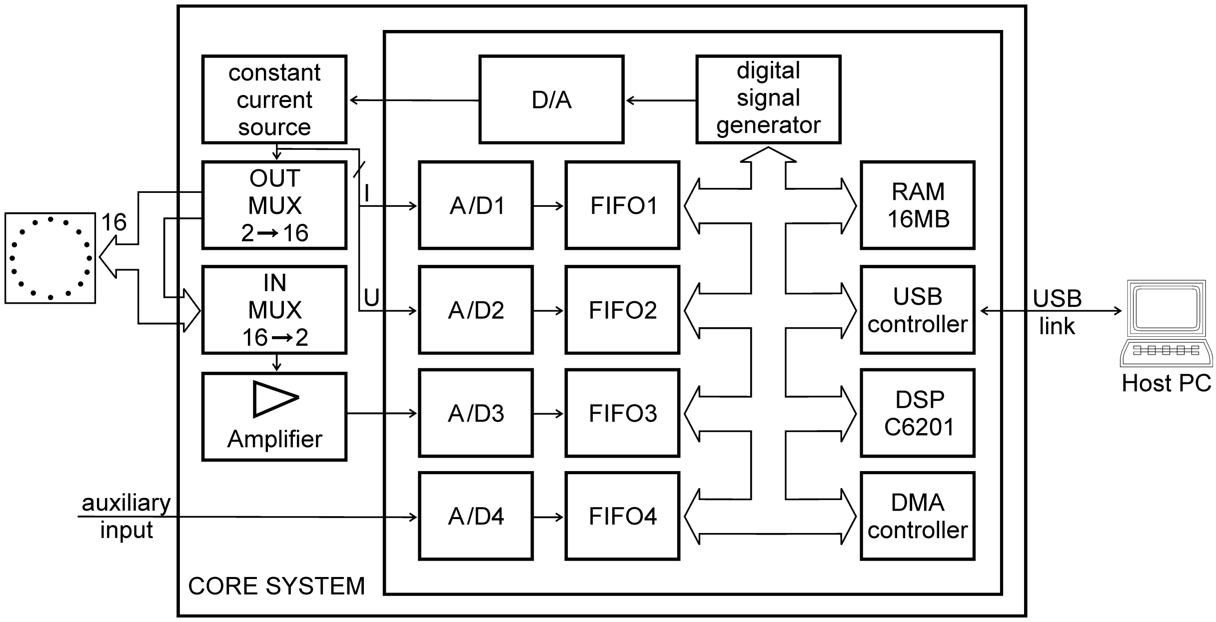

Fig. 1: The hardware setup of Goe-MF II EIT device.

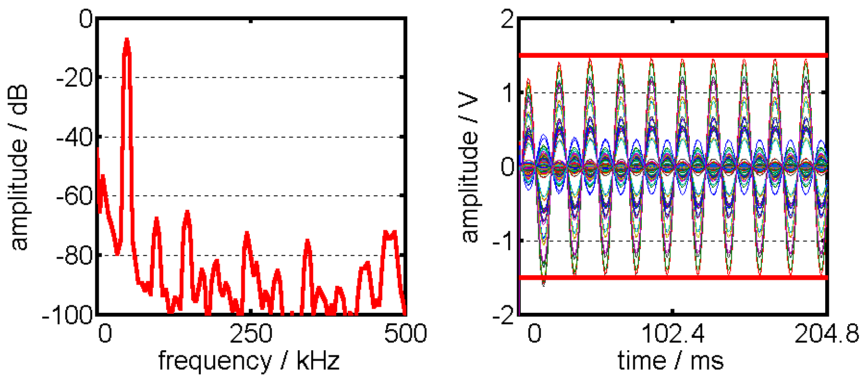

Fig. 2: Sampled AD-signals of 208 measuring electrode pairs in the frequency and time domain.

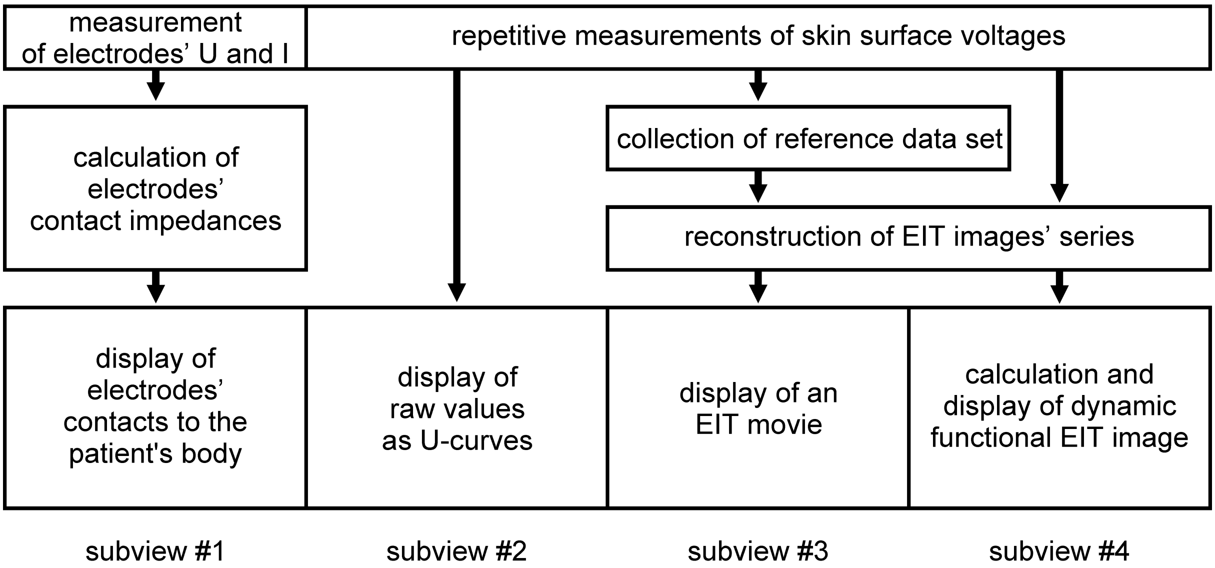

Fig. 3. Block diagram of online data processing in Goe-MF II software

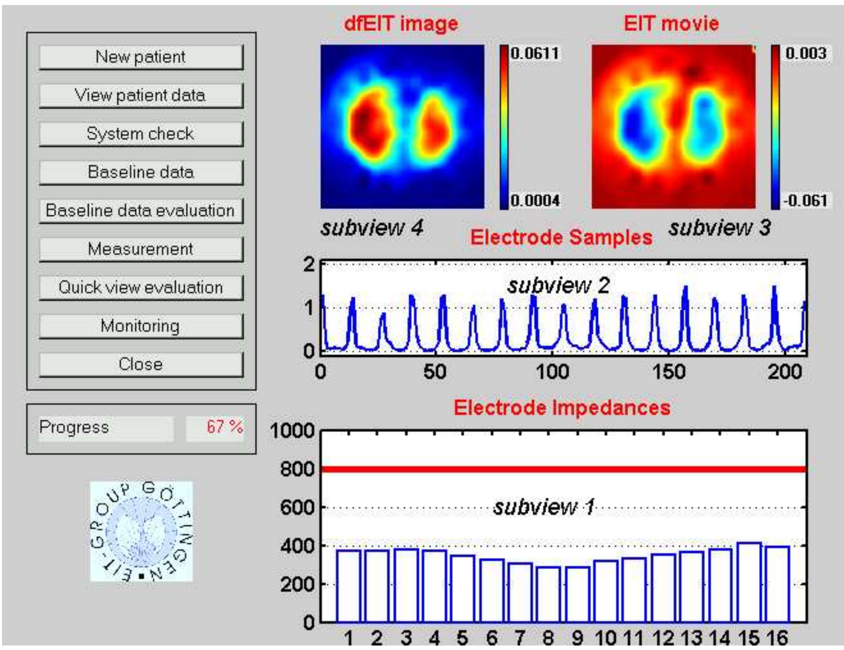

Fig. 4. PC screen of the Goe-MF II software displayed during data acquisition

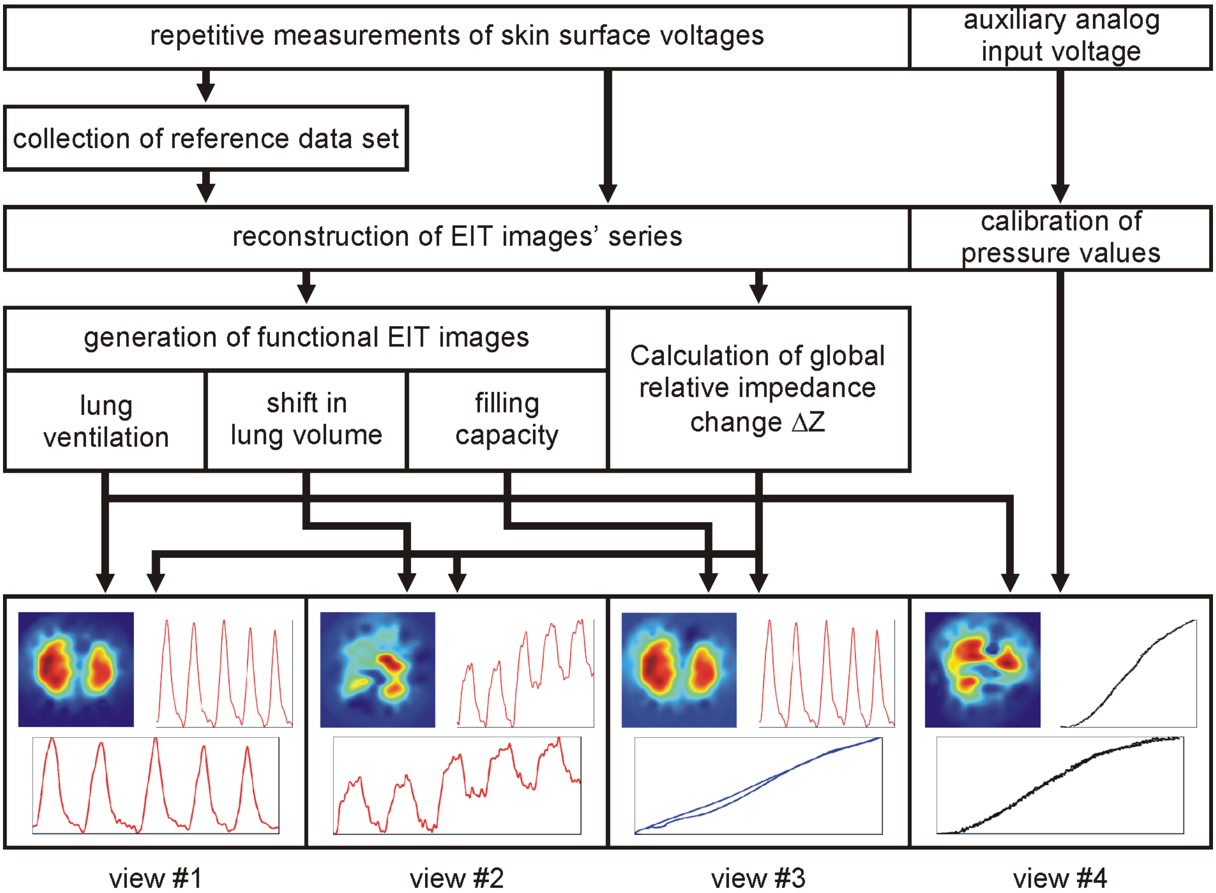

Fig. 5. Offline data processing in Goe-MF II Software.

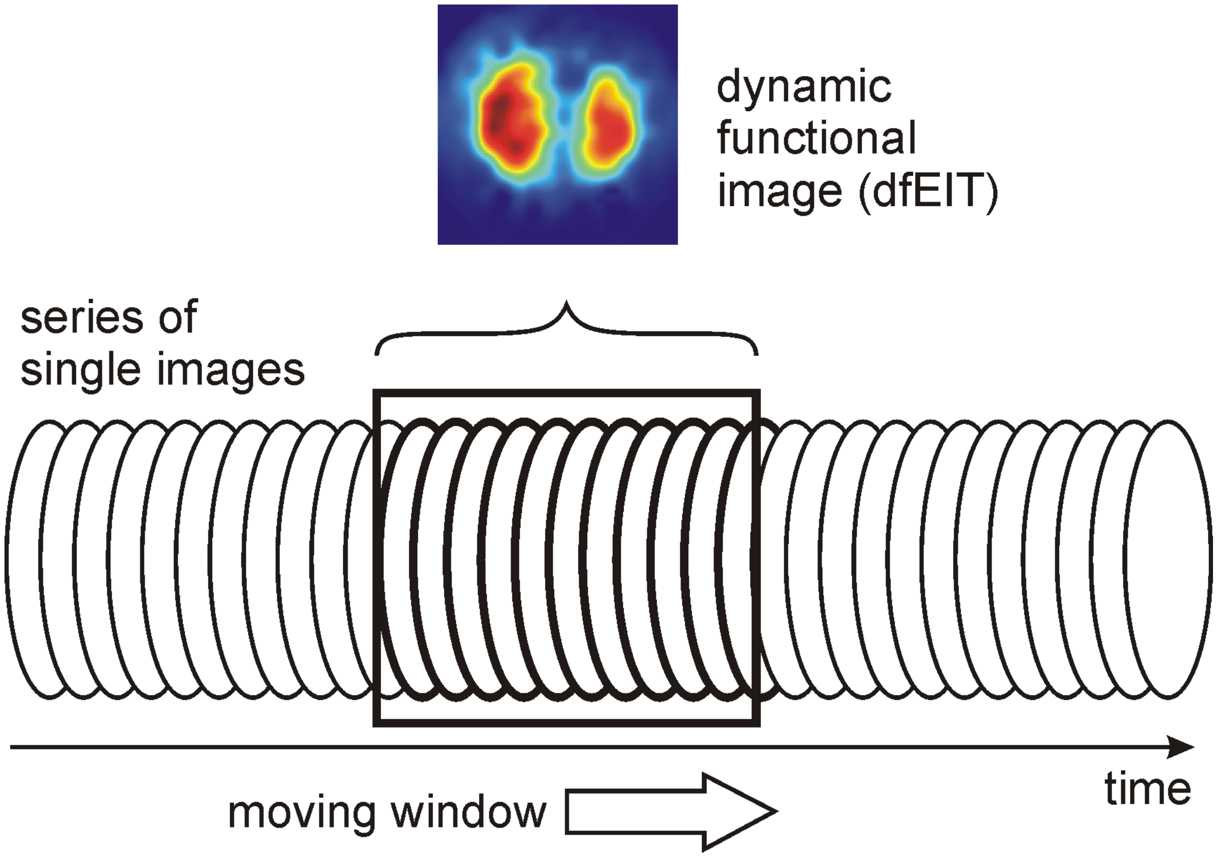

Fig. 6. Principle of dynamic, online generation of functional EIT images during EIT data acquisition.

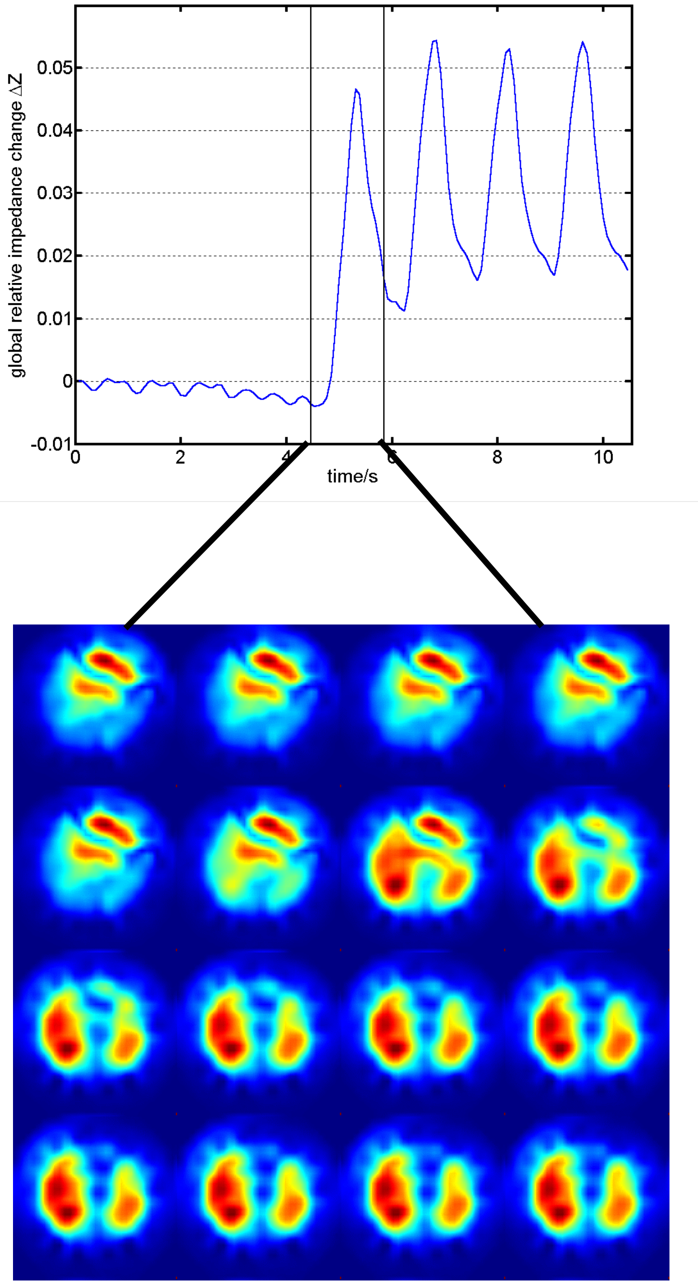

Fig. 7 a) Global time course of relative impedance change, and b) series of df-EIT images of a healthy volunteer performing the end-expiratory breath-hold maneuver followed by spontaneous breathing. Data acquisition performed at 13 Hz, only every third df-EIT image between solid vertical lines is shown.

Impressum

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