Head of the bed elevation angle recorder for intensive care unit

Maciej Krefft[a] and Aleksandra Zamaro-Michalska[b] and Wojciech M. Zabołotny[a] and Wojciech Zaworski[a] and Antoni Grzanka[a] and Tomasz Łazowski[b] and Mario Tavola[c] and Jacek Siewiera[d] and Małgorzata Mikaszewska-Sokolewicz[b]

[a]Institute of Electronic Systems, Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 Warszawa, Poland
[b]I Department of Anaesthesiology and Intensive Care, Medical University of Warsaw, ul. Lindley'a 4, 02-005 Warszawa, Poland
[c]Department of Anaesthesia and Intensive Care ASL3 Genovese, Genova, Italy
[d]Department of Anaesthesia and Intensive Care, District Hospital, Bolesławiec, Poland

ABSTRACT

This paper presents a recording system optimized for long term measurement of bed headrest elevation angle in the Intensive Care Unit. The continuous monitoring of this parameter allows to find the correlation between the patient's position in bed and the risk of the Ventilator Associated Pneumonia (VAP), a very serious problem in therapy of critically ill patients. Recorder might be be an important tool to evaluate the "care bundles" – sets of preventive procedures recommended for treatment of patients in the ICU.

Keywords: Bed headrest elevation measurement, Intensive care, Biomedical recording systems, Ventilator Associated Pneumonia

1. INTRODUCTION

Ventilator-associated pneumonia (VAP) is partially avoidable complication, it is the pneumonia that develops 48 hours or longer after endotracheal intubation and commencement of mechanical ventilation. Ventilator-associated pneumonia (VAP) results from the invasion of the airway and lung tissue by microorganisms. Endotracheal tube placement compromises upper and lower respiratory tract and allows oral and gastric secretions to enter the lower airways. Several activities have been postulated to prevent VAP and prevention guidelines (bundles) have been announced and published by many clinical scientific societies. One of postulated interventions, potentially preventing development of VAP is elevation of the head of the bed (HOBE) to the angle of 30 degrees. From the practical point of view it is impossible however to keep patients bed in this position for 24h a day because there are several daily performed procedures and activities when patient has to lay flat.

The incidence of VAP itself is poorly defined: there are reports of number of VAP cases per 1000 ventilation days or number cases of VAP diagnosed in month or year.

To our knowledge there were only mechano-electronical tools tested for real-time measurement and recording of HOBE in intensive care unit (ICU) so far. We developed handy, compact electronic device, which can operate autonomously or connected to the computer and record HOBE continuously. Continuous monitoring and recording of the headrest angle might deliver fair report of daily adherence to VAP prevention bundle.

Further author information: (Send correspondence to W.M.Z.)
W.M.Z.: E-mail: wzab@ise.pw.edu.pl, Telephone: +48 22 234 7717

2. CONTINUOUS MONITORING OF THE HEAD OF BED ELEVATION

The hospital beds are not routinely equipped with the system allowing to continuously monitor the elevation of the head of bed (headrest).

Position of the head of the bed can be monitored by simple tools like protractor and plumb line.[1] Recording is not continuous and operator dependent. There are devices using mechano-electronical methods for real time monitoring and recording HOBE using water sealed tubing connected to pressure transducer and bedside monitor. They have rather cumbersome setup and maintenance and require calibration (spirit level protractor).[2,3]

The alternative approach uses electronic accelerometers. The simplest variant uses 1-axis accelerometer and was developed by Horgan (patent US 7117607B2),[4] another one using 2-axis accelerometers was developed by Johnson and Clark (patent US WO 2011126800A2).[5]

We decided to use the 3-axis accelerometer. Device may work firmly mounted to the bed rest frame.

If we measure the vector of gravitational acceleration in the horizontal position of the bed and find the following components:

$$\vec{g_1} = (g_{1x}, g_{1y}, g_{1z}) \tag{1}$$

Then if the gravitational acceleration vector in the measured position is equal to:

$$\vec{g_2} = (g_{2x}, g_{2y}, g_{2z}) \tag{2}$$

we can easily find the angle between those two vectors according to the formula:

$$\alpha = acos\left(\frac{\vec{g_1} \cdot \vec{g_2}}{|\vec{g_1}|\,|\vec{g_2}|}\right) = acos\left(\frac{g_{1x}g_{2x} + g_{1y}g_{2y} + g_{1z}g_{2z}}{\sqrt{\left(g_{1x}^2 + g_{1y}^2 + g_{1z}^2\right)\left(g_{2x}^2 + g_{2y}^2 + g_{2z}^2\right)}}\right) \tag{3}$$

Our recording device records the components of the gravity acceleration vector and timestamps. The elevation angle may be calculated later on off-line in a computer processing the stored data. This allows to reduce significantly complexity of data processing in the recorder, and power consumption and enables longer device operating time (monitoring).

3. HARDWARE DESIGN

Overview of situation in the ICUs has shown, that two scenarios are possible. In the first one, there is a PC compatible computer available as a part of standard monitoring system and it is possible to connect an additional USB device to it. In the second case, no computer is available, and the recorder must operate fully autonomously. Basing on those scenarios two versions of the recorder have been designed. Both versions are placed in enclosures allowing to clean and disinfect the device according to the ICU hygienic requirements.

3.1 Elevation recorder as an USB peripheral device

In this configuration, shown in the Fig. 1, the measurement device can be extremely simplified. It consists only of the 3-axis electronic accelerometer LIS35D,[6] and the ATmega32U4 microcontroller[7] with a few supporting components. The USB interface provides the +5V power supply voltage which is later on reduced to +3.3V by the linear voltage regulator. Both microcontroller and the accelerometer are powered from the +3.3V voltage.

The accelerometer is controlled via the I^2C interface, and the same interface is used to read the acceleration vector components. New data are read every 125ms and transmitted to the PC.

The microcontroller firmware is written using the open source LUFA USB framework,[8] and implements the USB HID class device. Such approach allows to communicate with the recorder without installation of additional drivers, which for security reasons is especially important in case of computers being parts of the bedside monitoring system. The PC software is written in Java, and uses the javahidapi[9] library to assure communication with the USB HID device.

The PC software is portable and may run both on Linux machines and on MS Windows machines. The power supply is provided by the USB port of the host PC. The PC application averages received acceleration vector components, and writes results every 10 seconds to the file on disk. The output file is written in a CSV format, which allows further processing either with spreadsheet (e.g. MS Excel or OpenOffice Calc) or with dedicated analysis software.

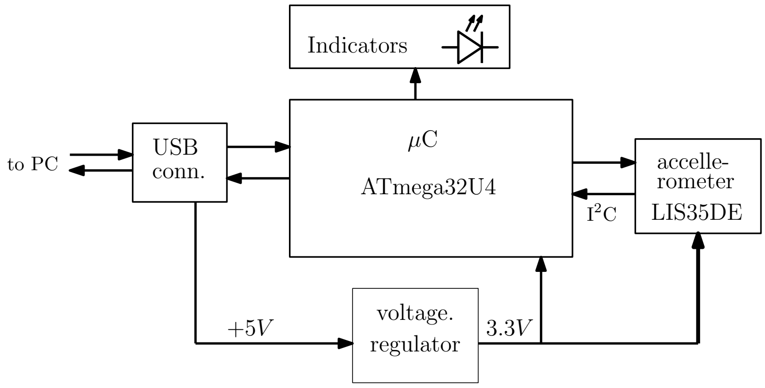

Figure 1. Simple elevation recorder, suitable for ward equipped with monitoring systems containing accessible PC-like computer.

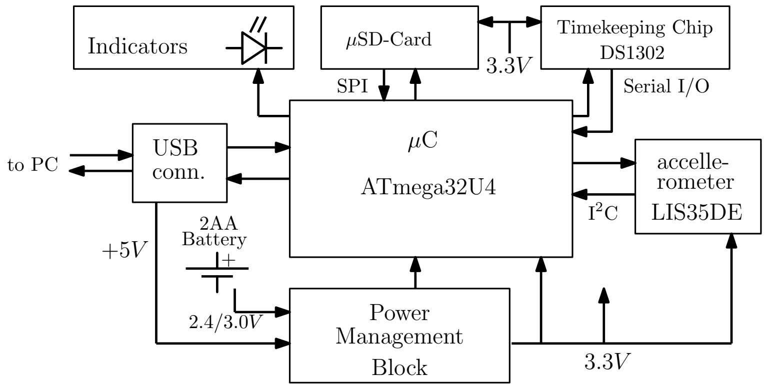

Figure 2. Extended elevation recorder, able to work in the autonomous mode.

3.2 Autonomous elevation recorder

The version of the system dedicated for hospital wards where no bedside PC computers are available is much more complicated. The block diagram of such configuration of the system is shown in the Fig. 2.

The heart of the system is, as in the simpler version, the ATmega32U4 microcontroller.[7] To allow timestamping of recorded data, the device is equipped with the realtime clock DS1302.[10] When the device is switched off, the operation of the realtime clock is backed by a separate, internal battery. The LIS35DE accelerometer[6] is, as previously, connected to the I^2C interface of the microcontroller. The recorded data are stored in a CSV file in the SD memory card formatted with the FAT filesystem.

To allow fully autonomous operation, in the recording mode the device is powered from the +3V battery or +2.4V Ni-MH rechargeable battery. To assure stable supply voltage, the voltage is boosted to the +5.5V using the DC-DC converter with MCP1640[11] chip, and further stabilized at +3.3V with the linear voltage regulator. The capacitors on the input and output of the linear regulator are big enough to assure stable output voltage during temporary increases of SD card power consumption due to writing of data.

When device, working in the recording mode, is switched off, the dedicated delay circuit is activated. The microcontroller is first notified about request to finish the recording, so it can correctly stop data acquisition, close file and unmount the filesystem. The power supply voltage is switched off after ca. 4 seconds delay, which is sufficient to complete the described shutdown procedure. Such approach prevents corruption of the filesystem and loss of data.

After recording is finished, the device may be connected to the USB port of the computer. The +5V supply voltage is stabilized at +3.3V by the linear voltage regulator. The microcontroller recognizes, that the power supply voltage is provided via the USB connector, and activates another mode of operation, in which the device emulates the USB FLASH disk. This allows to easily access recorded data and transfer them to the PC.

The firmware for the microcontroller is split into two parts. The first one is used in the recording mode, and is highly optimized regarding the power consumption. The microcontroller is put into sleep mode whenever possible. The data to be written to the SD memory card are first assembled in the RAM to minimize number of write accesses to the card. The routines supporting the FAT filesystem on the SD memory card are provided by the open source library written by Roland Riegel.[12]

The data from the accelerometer are stored every minute. Writing of data is confirmed by short flash of the blue LED. Correct operation of the device in the recording mode is confirmed by the short flash of the red LED every 5 seconds.

Fully charged rechargeable batteries, or new batteries are sufficient for more than 4 days of recording. When the battery voltage drops below +2.2V, the short acoustic signal is activated every 5 seconds. After low voltage signal is activated, the device may record data for at least 10 hours. This is important, when the person maintaining recorders is not available immediately.

The part of the firmware supporting the USB mode of operation is written using the open source LUFA USB framework,[8] and implements the USB Mass Storage class device. Integration of the LUFA framework with the SD memory card driver was based on the open source project "Teensy2 USB Mass Storage with an SD card".[13]

4. SOFTWARE FOR OFF-LINE ANALYSIS

Both versions of the system store data in the CSV format, either directly on the PC disk, or on the SD memory card, which may be further connected as an USB Flash disk to the PC. Therefore the acquired data may be read and processed directly by the spreadsheet program. However to simplify data analysis, the dedicated software was written, which integrates necessary functionalities.

4.1 Functional description of TIAN – software for off-line analysis

Application TIAN is developed with Eclipse framework. It is basically developed as a window application for Windows XP/7 operating systems and requires Java Runtime Environment (JRE) to work properly.

However, since it uses the Java technology, it can also run under control of other operating systems (e.g. Linux or Mac OS), for which the JRE is available.

Different free libraries (available under LGPL license) JFreeChart,[14] iTtext[15] etc. were used during development of TIAN application. Additionally GWT Designer[16] was used to support windows-like layout of software.

Application allows user to manage database of patients including data concerning head of bed elevation measurement. User can intuitively add, change or remove patient's records, and import measurement data associated with those records.

There is also a possibility to perform basic analyses required in this type of measurement. Time analysis allows to calculate duration of time when the head of bed elevation is in the specified range of angles.

Application supports also detection of rapid changes of elevation – in this case user may define the required minimal change of elevation, which should be detected in the recording.

Software includes graphic visualization of measurement (time trend of elevation) with possibility to change both range of the X axis (time) and range of the Y axis (elevation).

Alternative mode of data display is represented by a simple time list of elevation changes, which is calculated on the basis of measurement data (coordinates of the tilt vector). Before the calculation is started, user needs to provide two files in the CSV format (comma separated value). The first one with the measurement data, and the second one with at least two calibration measurements, recorded in the horizontal position of the headrest.

Application supports also exporting of the graph and the time list in the PDF format.

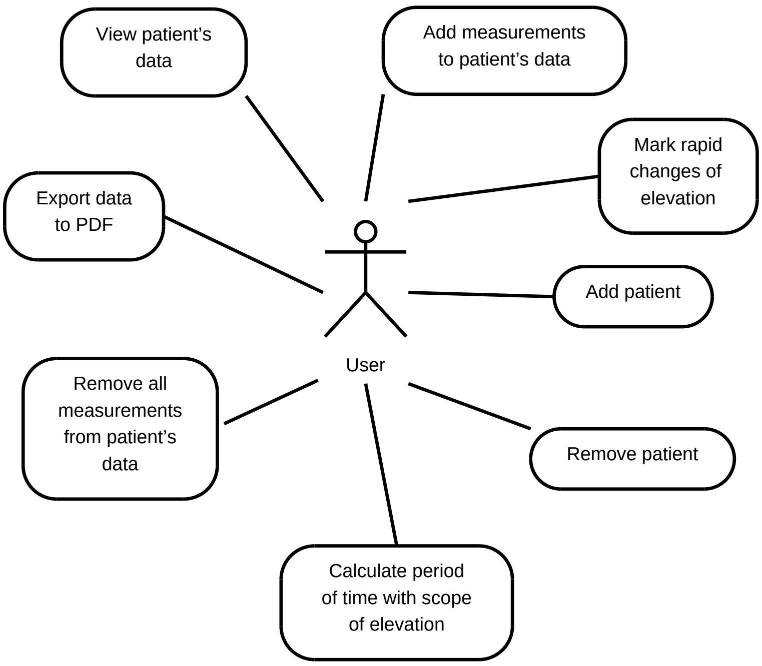

Figure 3. Use cases diagram for TIAN software

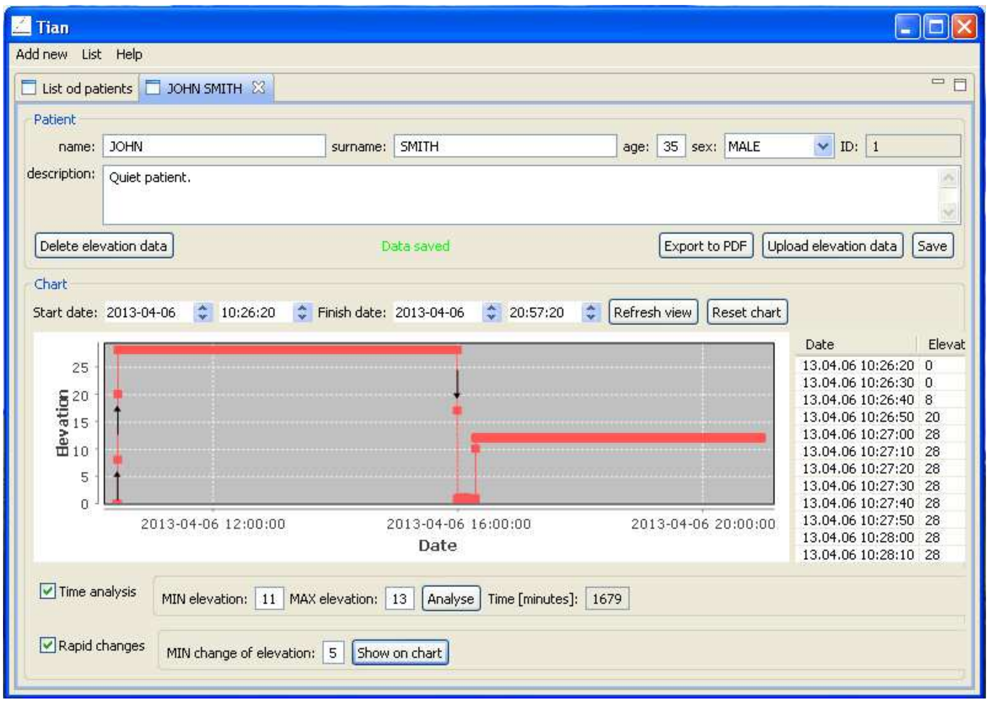

Figure 4. View of the main window of the TIAN software

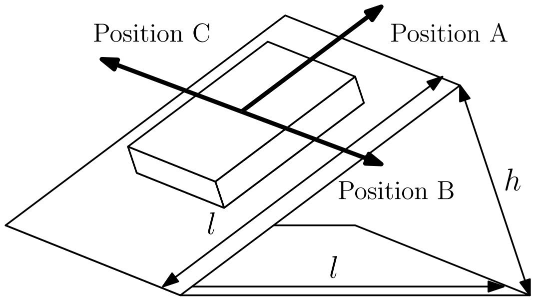

Figure 5. Test stand for testing of the elevation angle recorder.

Table 1. Results of testing of the head of bed elevation recorder. The set angle was calculated according to the equation (4) for l=304 mm. The measured angle was calculated according to the equation (3). Different recorder positions are marked according to Fig. 5.

Position of the recorder	h	g_x	g_y	g_z	angle set	angle measured	angle error
Position A	0.000	0.217	-2.412	55.839	calibration for 0 degrees		
	71.000	0.656	11.295	54.299	13.412	14.230	-0.818
	112.000	0.563	18.690	52.160	21.230	22.189	-0.959
	145.000	0.745	24.304	49.691	27.594	28.540	-0.946
	198.000	0.933	33.051	44.164	38.011	39.288	-1.277
Position B	0.000	-0.520	-2.760	55.868	calibration for 0 degrees		
	71.000	-13.871	-2.045	54.174	13.412	13.835	-0.423
	110.000	-20.914	-1.865	52.000	20.847	21.377	-0.531
	145.000	-26.882	-1.271	49.286	27.594	28.099	-0.505
	197.000	-35.425	-0.136	43.787	37.812	38.518	-0.707
Position C	0.000	0.499	-2.878	55.890	calibration for 0 degrees		
	71.000	13.607	-2.440	54.280	13.412	13.554	-0.142
	111.000	20.911	-2.221	52.122	21.038	21.338	-0.299
	145.000	26.884	-2.074	49.439	27.594	28.009	-0.415
	194.000	35.179	-1.965	44.338	37.214	37.893	-0.679

5. RESULTS

The quality of elevation measurement was controlled using the test stand, shown in the Fig. 5. The angle between the horizontal plane and the test plane was calculated according to the formula:

$$\alpha_{set} = 2\arcsin\left(\frac{h}{2l}\right) \tag{4}$$

Results of measurement are summarized in the Table 1. It can be seen, that maximum measurement error was less than 1.3 degrees, and that the recorder works reliably, if it is fixed in any of tested positions.

Currently 8 copies of the simplified recorder and 6 copies of the extended recorder have been used in the clinical practice in hospitals in Warsaw (Poland) and in Lecco (Italy). The extended version of the recorder, attached to the headrest of the hospital bed is shown in the Figure 6.

Sample results calculated from the recorded data are shown in the Fig. 7

6. DISCUSSION

Nosocomial infections, particularly those caused by multi-drug-resistant pathogens, are currently among the main problems of healthcare systems worldwide. There are two main reasons why this issue applies particularly to ICUs (Intensive Care Units):

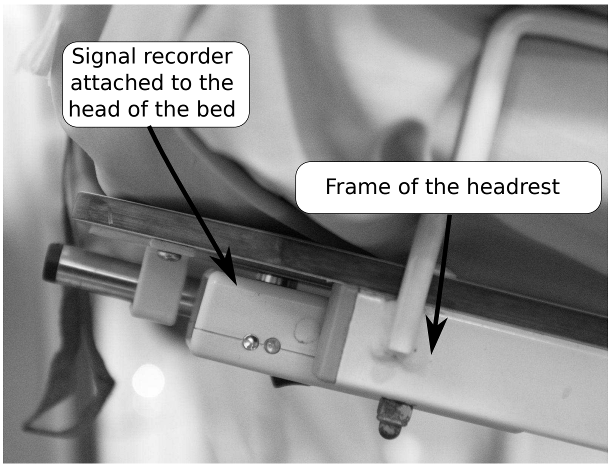

Figure 6. The extended version of the recorder attached to the head of the hospital bed.

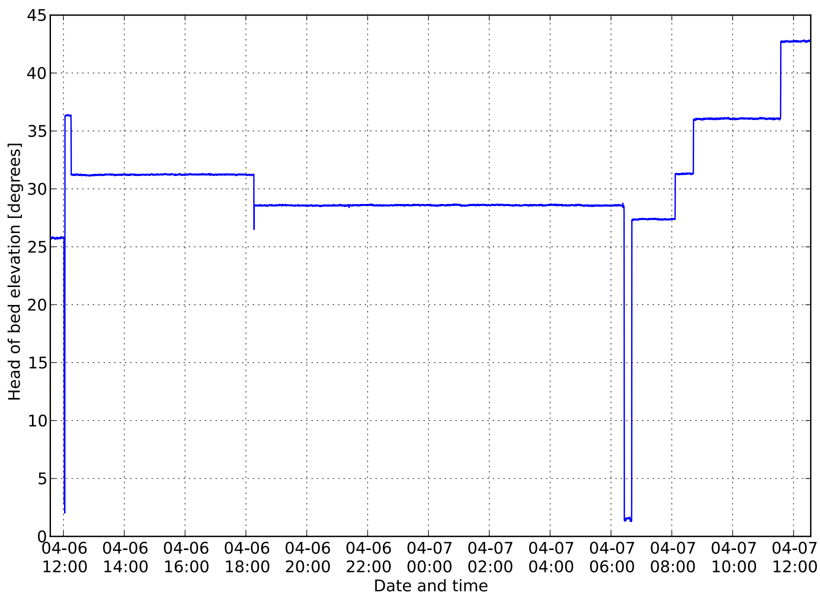

Figure 7. Sample recording of the head of bed elevation angle.

- On those wards are hospitalized patients with severe infections.
- A broad application of antibiotic therapy at ICUs causes a selection of multi-drug-resistant pathogens.

Research on new antibiotics is currently limited for various reasons. An ever more frequent isolation of multi-drug-resistant pathogens, in particular gram-negative bacteria, in hospitalized patients raises concern that medicine will more and more often face a situation of an infection that will be impossible to treat. Pneumonia is one of the most common hospital-acquired infections. And pneumonia associated with intubation and mechanical ventilation (VAP - ventilator-associated pneumonia) is the most common infection in critically ill patients (Intensive Care Units' patients). According to the data published in the report from 2010 covering 125 ICUs in Italy, the incidence of this complication is 8.9/1000 days on ventilator. More than 20% of the cases were caused by multi-drug-resistant pathogens.[17,18] Therefore the treatment of VAP is very difficult and this infection is still burdened with high mortality rate – from 30 to 50%.[17,19] Occurrence of pneumonia associated with mechanical ventilation extends the time of mechanical ventilation, length of patient's stay in Intensive Care Unit and length of stay in the hospital after discharging from ICU.[20] It was also estimated that the occurrence of VAP significantly increases hospital costs from 2 to 7 times comparing to the ICU stay with uncomplicated mechanical ventilation (VAP occurrence increases the costs of hospitalization by approximately 40,000 $).[21]

Therefore, at present, particular attention is paid to prevention of VAP, which is based on the so-called "care bundles" (according to the guidelines and recommendations of the International, European and Polish Societies of Anaesthesiology and Intensive Care). The bundle is a set of activities which, when implemented together, are more effective than implemented separately.[22]

The most commonly used respiratory package proposed by Institute for Healthcare Improvement consists of five key elements and involves the simultaneous application of: everyday oral hygiene with solution of chlorhexydin,[23–25] bed's headrest elevation of 30-45 degrees,[26–30] daily discontinuation of sedation and evaluation of the patient's readiness to detachment from respirator,[30,31] prevention of stress ulcer bleeding[30,32] and deep vein thrombosis prophylaxis.[30,33] The first two elements of the package relate directly to the pathogenesis of VAP. The pathogenesis of VAP is considered to be the gastroesophageal reflux as well as the leakage of infected oral secretions from the oropharynx into the respiratory tract.[34–38] Critically ill patients require intubation and mechanical ventilation, and also require feeding. The preferred way of feeding is the one which resembles physiological, eg. enteral nutrition via nasogastric tube. There is physiological bacterial flora in oropharynx and intestines. Gastroesophageal reflux occurs frequently in such patients. That way some part of gastric contents enters the oropharynx and then leaks through micro-apertures around the cuff of the tracheal tube into the trachea. Furthermore, in the lack of proper oral hygiene, bacteria multiply in the oropharynx and the infected oral secretions can leak into the respiratory tract.

Patients who are positioned horizontally during mechanical ventilation are more prone to gastroesophageal reflux, hence the patient's positioning is one of the issues that may have a significant impact on VAP occurrence. Previously published studies have shown that patients ventilated in a supine position are three times more likely to get pneumonia than patients ventilated in the semi-recumbent position.[26] Indeed the semirecumbent position prevents aspiration of infected oral secretions, which is presumably the initiating factor in most cases of VAP. All studies that assessed the risk of leakage of gastric contents into the respiratory tract as well as VAP occurrence depending on the patient's position were controlled clinical researches where patients were randomly assigned to one of the groups (supine or semi-recumbent position of 45 degrees) and ventilated at a given position for a period of time (e.g. 3 days).[26,34–38]

In spite of the proven more frequent occurrence of VAP in patients ventilated in the supine position, the recommendations on the semi-recumbent position remain debatable.[39–43] This stems from lack of scientific reports of continuous assessment of the patient's position during the whole period of mechanical ventilation. The position of a mechanically ventilated patient has to be changed many times during the day due to the need of carrying out a number of ICU procedures (patients' personal hygiene, posting central venous catheters, taking hemodynamic measurements, chest X-rays, reintubation etc).

To sum up, a permanent ventilation of patients in one position is impossible to carry out in the circumstances of everyday clinical practices at an ICU, while the 45 degrees elevation suggested in the above-described researches is often difficult to achieve in the everyday care of the patient. It has not yet been assessed what elevation of the bed's headrest from the horizontal position is a protective marker for VAP occurrence and what is the minimal period of time during 24 hours in which the patient should be in that position. It has not yet been tested, most probably due to the lack of a technology enabling constant monitoring of the patient during the process of mechanical ventilation. Creating a device which would constantly monitor patient's position allows to assess the influence of the patient's position throughout the period of mechanical ventilation on the risk of VAP occurrence.

This solves the problem of an impartial assessment of the influence of this element of the package on the risk of VAP occurrence, as this had previously been the only element of the package whose impartial verification of application was impossible to conduct.

The assessment of the four remaining elements of the package does not cause any problems. If a correlation between the patient's position and the frequency of VAP is confirmed, it may be another element of constantly monitoring critically ill patients which will allow to avoid complications burdened with high mortality rate and will improve the clinical practice in intensive care.

The usefulness of the device is studied at the moment in several ICUs in Poland and Italy and the final results will be presented in doctoral dissertation by Dr Zamaro-Michalska in the nearest future.

7. CONCLUSIONS

The elevation angle recorders presented in this paper are well suited for continuous monitoring of the head of the bed elevation in the hospital conditions.

Depending on the availability of the USB equipped computer in the bedside monitoring system, one of two versions of recorder may be selected:

- Simplified recorder, with power supply provided via USB interface and transmitting data directly to the computer.
- Extended autonomous recorder, allowing to perform up to 4 days measurements in the autonomous mode, before battery replacement. The data are stored on the SD memory card, and may be later transferred to the PC computer.

Both versions of the recorders have been successfully tested in clinical practice, and allowed to collect long term recordings of the head of the bed elevation for many patients.

We are convinced that this study will bring very valuable tool as well as clinically useful information about impact of VAP prevention bundles on the incidence and clinical consequences of VAP.

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