ELECTRONICALLY EQUIPPED BEDS

USED IN SLEEP MEDICINE

DATA AQUISTION METHODS AND ELECTRONIC SENSING PRINCIPLES

Raul Kala

The aim of the book

Aquiring signals from the sleeping patient is a very difficult task because of the wish not to disturb the patient’s sleep and the weaknesses of the detectable signals. Measuring patient’s sleep in an unobtrusive way can be done with non-contact data aquisition methods but the drawback is that not all important parameters can be measured and the detectable signals are weaker than those detected with electrodes. This is a serious problem when information about REM and NREM states is required. However, the problem can be simplified when information about only heart rate and breathing rate is needed.Heart rate and breathing rate give a lot of valuable information about the patient’s health status and specially about the occurance of obstructive sleep apnea. This information can be used in many different ways, also in long term monitoring.

The aim of the book is to offer scientists and engineers a critical overview about electronically equipped beds and mattresses used in sleep medicine for non-contact heart rate and breathing rate measurement. The book consists of 5 chapters what describe the history and data aquistion methods of electronically equipped beds/mattresses and the usage of them in smart environments. All of these chapters are based on describing the physical effects of the sensors.

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Introduction

Sleep medicine is a very slowly evolving field of science. The new devices what could be used in sleep medicine find their usage very slowly. This happens mainly because there is a paradigm what tells us that for sleep medicine/research you need a PSG device. The usage of the PSG is a complicated task because it takes a lot of time to install all the sensors to the patient and these sensors might disturb the patient's sleep. Therefore there is growing interest in the usage of non-contact long term monitoring devices. This book shows how different electronic sensors installed into the bed or mattress enable long term non-contact monitoring of the breathing and heart rate. Here is a brief overview about the information about the chapters found in the book.

Chapter 1, Historical overview about electronically equipped beds used in sleep medicine

This is the shortest chapter of the book. This chapter was made in order to show the interested reader what has been done previously. Sometimes a new thing can be a well forgotten old thing. Reading old patent descriptions can be very revealing because the technological progress opens new possibilites for old methods.

Chapter 2, The sensing principles and data aquisition methods of electronically equipped beds used in sleep medicine

This chapter describes how smart beds and mattresses are designed. Reading this chapter requires strong backround knowledge in electronics. Therefore it is advised to read books about instrumentation, measurement and biomedical engineering. This long chapter describes only most common sensing principles and data aquisition methods and the reader should keep in mind that the list of sensing principles and data aquisition methods is growing in time.

Chapter 3, Electronically equipped beds used in smart environments

Today the patient lives in an environment what tracks his everyday activities, stores the data in a cloud and uses it for learning and acting. This also means that the patient is 24/7 under the surveillance and there are problems with identity theft and data privacy. On the other hand, information about the lifestyle can make the treatment process easier. This chapter describes non-contact room based data aquisition methods(See subchapter 5.3). The first sub-chapter describes two very different smart environment concepts: the Ambient Assisted Living concept and the Smart Home concept.The second sub-chapter describes some electronically equipped beds specially designed for the hospital environment.

Chapter 4, Remote and ubiquitous sleep monitoring systems

This chapter describes how to monitor the sleeping patient when the sensors are outside the bed. This can be a very useful option when there are many patients to be monitored. For example one single radar can monitor all the patients inside the ward. This chapter does not include IR radiation measurement because IR radiation measurement is already described in subchapter 2.2.4.In addition to the heart and breathing rate measurement the usage of remote and ubiquitous monitors helps to monitor the life style, health status, sleep-wake pattern and emergencies. The radar and ultrasound sensors can be easily added to the Smart House (See subchapter 3.1.3) or used for detecting the bed exits (See chapter 5).

Chapter 5, Bed exit detection systems

So far the book has concentrated on non-conctact sleep monitoring but curing the patient is a complex process and sleep monitoring only one part of it. Although it may seem simple, there are situations where knowledge about the presence of the patient is of paramount importance. For example the patient may suffer from some kind of trauma or disease and for some un-known reason fall out of the bed. Within the worsest cases the patient may lose consciousness or fall and get some bone fracture and not be able to call any help but there might be situations where every minute counts. Therefore beds being able to detect the presence of the patient or being able to understand if the patient left the bed normally or fell out of the bed are very important, specially in the hospitals.

This chapter gives an overview about different bed exit detection systems and discusses about some of the most common technical solutions. The emphasis is on the choice of sensors and the usage of nurse call systems. The systems described are classified into 3 major classes: person-based systems, bed-based systems and room-based systems. Person-based systems are systems where some kind of sensor is somehow connected to the patient. Bed-based systems are systems where the sensor is connected to the bed. If the only aim is to detect the presence or fall of the patient when this type of system is the most optimal to design. Room-based systems are systems where the sensor is located somewhere inside the room and can be considered as a part of Ambient Assisted Living concept and can be reminded in the sub-chapter 3.1.2. Also, the room-based systems can be defined as remote and ubiquitous sleep monitoring systems and therefore it is recomended to re-visit the chapter 4. The nurse call feature is mentioned because although the nurse call system as such is a complicated system what can be realised in many different ways, it still helps to track the patient and sometimes this extra redundancy might be needed.

CONTENTS

Chapter 1

HISTORICAL OVERVIEW ABOUT ELECTRONICALLY EQUIPPED BEDS USED IN SLEEP MEDICINE

Historical overview about electronically equipped beds

Since the time devices required to detect, ampilfy and process electric signals became available, scientists and engineers started to add electronics to the beds. Possibly the first attempt to equip a bed with electronics dates back to March 18, 1912 then A.R. Gibson and G.H.Ferguson applied for a patent – "Vibratory bed"(Gibson and Ferguson,1912). They designed a laterally vibrating bed and advised to use any kind of electric motor. The usage of electronically equipped beds in science and sleep medicine started in 1914 then Szymansky started research about nocturnal activity (Stampi, 1992) and designed spring-suspended beds and chairs in order to record all kind of movements from motility to respiration(Stampi, 1992).Since from the beggining of equipping beds with electronics, two different paths have evolved and these paths continue even today: bed exit detection systems and beds equipped with electronics for diagnostic purposes. Early bed exit systems were designed by J. Applegarth and M. Ferry (J. Applegarth and M. Ferry, 1941) and D.E. Belich (D.E. Belich,1950) but the list is not complete. The first electronically equipped beds used in sleep medicine, designed by Johnson and Swan in 1930 (Johnson and Swan,1930),Stanley and Tescher in 1931(Stanley and Tescher, 1931), Kleitman in 1932 (Crisp et. al, 1970) and Cox and Marley in 1959 (Cox and Marley, 1959) were based on transforming bedspring movement into electrical signals. During many decades of research 8 data aqusition methods have evolved based on the usage of Foucalt cardiography, photo-plethysmo-graphic principle, air mattresses, electronic textiles and capacitive sensors, static charge sensitive bed, pressure measurement, hydraulic measurement and temperature measurement. As a part of the smart house paradigm, remote sleeping status tracking devices and systems have been developed. These systems include the usage or radar, infrared light and ultrasound. It is obvious that in the near future remote sleep status tracking systems will become a principal component of a wealthy lifestyle just like pulse rate watches are today.

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Chapter 2

THE SENSING PRINCIPLES AND DATA AQUISITION METHODS OF ELECTRONICALLY EQUIPPED BEDS USED IN SLEEP MEDICINE

2.1 The origin of the signals and the sensing principles

2.1.1 What is sleep ?

So far science has given very little information about what is sleep and why we sleep but a huge amount of data what happends then a human or animal doesn't get enough sleep. Existing theories about the meaning and function of sleep are incomplete being focused on small set of symptoms or parameters and there is no great unifing theory that would explain these fundamental questions in phylogeny and ontogenesis. In the article written by Assefa and colleagues (Assefa et al., 2015) a table of 13 different theories, the authors and hypothesis and drwabacks and strengths is given and surely this list is not complete. It has to be mentioned that there is one theory, based on the AIM model (A – activation, I-input-output gating, M-modulation) that maps all counsciuosness states, including wake, NREM and REM, into one 3-dimentional state space(Hobson, 2009).With the help of this model different states of consciusness and diseases are related to each other with continous variables. Going into more detail, in 2009 Hobson (Hobson, 2009) wrote an article where he proposed an idea that REM sleep might be a protoconscious state: "*providing virtual reality model of the world that is of functional use to the development and maintainance of waking consciousness.*" This theory has at least one drawback, mentioned by the author: "*The model cannot yet explain the regional differences in brain activity that distinguish REM sleep from waking.*" Also it has to be mentioned that among all of those 13 different theories about sleep lies one theory what attempts to unify sleep, torpor and continous wakefulness with the energy allocation optimization(Schmidt, 2014).

2.1.2 A brief history of sleep medicine

With the help of electronic measurement methods, changes of electrical activity in many organs, mainly heart and brain, during sleep have been well documented and described. The first polysomonographic signals recorded from the sleeping patient originate from Alfred Loomis and his colleagues in 1935(Loomis, 1935). During the all-night-long sleep recordings described in Science in 1935, Loomis and colleagues recorded EEG, heartbeat, respiration, bed movement and bedroom noises(Loomis, 1935). Two years later, in 1937, Loomis and colleagues published an article "Cerebral states during sleep, as studied by human brain potentials" there they described 5 NREM stages (later studies revealed that there are 4 NREM stages) and presented the results in hypnogram(Loomis et al., 1937). In 1953 Aserinsky and Kleitman published an article "Regularly Occurring Periods of Eye Motility, and Concomitant Phenomena,During Sleep", a milestone in the sleep medicine history because it defined the REM sleep(Aserinsky and Kleitman, 1953). In 1957 Dement and Kleitman published an article there they described normal human repeating sleep cycle together with 4 NREM and one REM stages(Dement and Kleitman, 1957).

2.1.3 Sleep architecture: stages and cycles

There are two types of sleep, NREM and REM sleep and the NREM sleep is further divided into 4 stages: NREM 1, NREM 2, NREM 3 and NREM 4. The first two stages, NREM 1 and NREM 2 are called light sleep and stages NREM 3 and NREM 4 are called deep sleep or slow wave sleep because during these stages the EEG signals have low freqyency and high amplitude. Usually sleep starts from the transition from wake state to NREM 1, then NREM 2, NREM 3 and NREM 4, and sometimes moves back into NREM 2, before reaching REM sleep and then moving into deep sleep and then light sleep. Typically NREM stages take approximately 90 minutes. Deep sleep dominates during the first third of sleeptime, REM sleep stages dominate during the last third of the night. A typical healthy adult experiences 5-7 sleep cycles during 8 hours of sleep(Kryger,Roth and Dement, 1989). In order to get a complete overview about the sleep structure the transitions from different sleep states and stages are drawn on a graph, called hypnogram. Figure.1 represents the hypnogram of the typical adult sleeping patient.

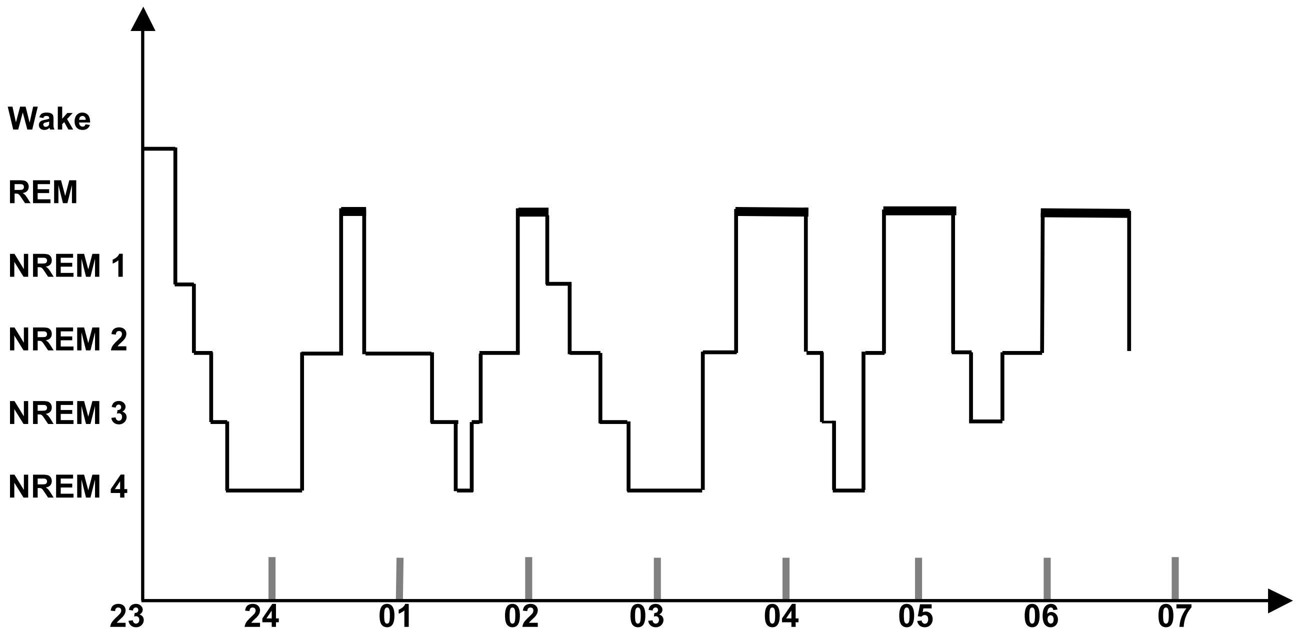

Figure. 1.The hypnogram of the typical adult sleeping patient.

The structure of sleep changes with age and is affected with environmental factors like temperature(Kryger,Roth and Dement, 1989). Also, the sleep stages are related to the circadian rhythms and this has to be taken into account because big changes in normal day-night cycle may distract the ability to get some sleep when needed. Abnormal sleep structure and/or not enough sleep causes a lot of health problems, including loss of memory and attention disorders(Vuohelainen, 2001). Therefore it is vital to sleep approximately 8 hours. According to M.Veldi(Veldi, 2009) a normal adult needs 7-8 hours of sleep of which some 20% is deep sleep and some 20% is REM sleep. Finally one has to remember that some people are “morning type” and some people are “night type” and because of this people’s most effective work time, the time to get sleepy and wake up are different. The sleep structure may differ among the members of the family or even between the twins(Veldi and Paavle, 2012). It is also important to notice that the sleep structure can get easily dirsupted by medicaments and/or some types of food or alcohol. Therefore it is wise to check the morning, day and evening menu and make some changes, for example stop drinking coffee 4-6 hours before going to bed because tablets can’t be a long-time solution for bad sleep(Vuohelainen, 2001).

2.1.4 Sleep monitoring devices and methods

Sleep monitoring started with the recording of EEG signals and reached it's peak with the development of the polysomnograph (PSG), a device for recording many signals simultaneously from the sleeping patient. This is a research based approach – it gives a lot of valuable information about the patient's health status but it is difficult to set up because installing many electrodes takes much time and also the body being in contact with electrodes can easily disrupt sleep. Therefore engineers and scientists have developed many different devices for sleep monitoring and theraphy and these can be found on numerous amounts of articles.In order to save the reader from too many details some review articles are introduced.This literature covers many aspects, from small general review level(Kala, 2012) to more detailed level(Verbraecken,2013). Also, there is good overview literature about the devices used in animal research and rest-activity monitorings(Deboer, 2007).
From the technical point of view all existing sleep medicine devices can be classified into 3 big classes: the devices what are connected to the body, smart environment and image aquisition devices used in the hospitals. Considering the fact that very often electronic devices are connected to the internet and / or store their data in the cloud, new dimensions have to be added. For example today many people like to control their e-environment with smart phones. This brings along a lot of data and signal processing and also problems with data security,verification and storage.

Devices what are connected to the body
There are many different types of electronic sleep medicine devices what can be connected to the body. Considering the size and complexity, the devices can be classified as wearable and stationary. Wearable devices are smaller and record less signals with lower quality but they have the ability to be worn 24/7.These devices are for example Headset, Actigraph, Pulse Oxymeter(SpO_2) and Vest(equipped with sensors and/or actuators). These devices help to gather data about heart rate, breathing rate and some other signals outside the hospital.Stationary devices are big in size and complex in design and therefore good for research. These devices are for example the polysomnograph (PSG) and car driving simulation system named DASS(Veldi, 2009).

Smart environment
The smart environment consists of sensors and actuators installed into the environment.
In sleep medicine the smart environment can be defined as the usage of different electronically equipped beds and pillows together with ambient assisted living devices, smart house or smart hospital. These aspects are described in chapters 3 and chapter 4. Chapter 3 describes smart environments and smart networked mattresses and chapter 4 describes remote and ubiquitous monitoring devices. The smart environments record easily detectable signals like heart rate and breathing rate in a non-contact way, without connecting any electrodes to the body. Therefore smart environments are not suitable for dignosing any disease but can be used for monitoring health status and collecting long term data.

Image aquisition devices
There are many review articles about using different brain imaging devices in sleep medicine(Dang-Vu et al., 2010; Drummond et al., 2004; Strauss and Burgoyne, 2008, Zimmerman and Aloia, 2006). Sleep has been studied with all kind of image aquisition devices, for example with fMRI(Redcay et al., 2007), MRI(Moon et al., 2010), NIRS(Fantini et al., 2003), PET(Maquet, 2000), and MEG(Dehghani, Cash and Halgren, 2011).Also multimodal studies have been conducted(Liu, Ding and He, 2006). This list is not exhaustive.

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2.2 Optic effect measurement based electronic beds

2.2.1 Introduction

2.2.2 Photoplethysmographic method based beds

2.2.3 Fiber optic sensors based beds

2.2.4 body’s IR radiation measurement based beds

2.2.1 Introduction

In sleep medicine 3 different optic methods are used for measuring the heart rate and breathing rate. All of these methods are similiar according to the principle but different according to the build-up.These methods use photoplethysmography, fiber optics and body’s IR radiation spectra measurement.Optic methods have their specialities but are also sensitive to body movements.Therefore these methods are not widespread. However, devices using these methods are simple to design and cheap to build. The use of PPG or fiber optic sensors requires that the patient is in contact with the sensor. Measuring body’s IR radiation can be done in a non-contact way, from the distance and therefore find usage in remote monitoring and bed exit detection systems (see chapter 5).

2.2.2 Photoplethysmographic method based beds

measures
- heart rate
- breathing rate

design principle
- LED technoloogy

Photoplethysmogrpahy is a method where red or infrared (IR) light is directed to the measurable tissue and the changes of the light intensity caused by the changes of the tissue are detected via light transmission or reflectance from the tissue.For long time PPG method was used in the pulse oxymetry for detecting SpO_2 and HR readings. In pulse oxymetry a sensor is placed around the finger or attached to the ear lobe. Because this is a method there the sensor is hardly clamped to the measurable tissue, it gives very accurate readings. Unfortunately wearing the PPG sensor is uncomfortable and disturbs patient’s sleep during PSG investigation. Therefore non-contact PPG methods have been developed. In non-contact PPG measurements a sensor consisting of a LED and a photodetector is placed close to the measurable tissue, for example under the sheet or mattress there changes in body movements cause mattress movements that modulate the light intensity. The following describes the usage of non-contact PPG data aquisition method being applied to the beds and pillows.
The beds equipped with PPG sensors have been used for the detection of HR(Maki et al., 2010; Wong et al., 2009; Gu et al., 2009; Wong et al., 2010; Brüser et al., 2012) and BR(Brüser et al., 2010; Maki et al., 2010) and even an attempt to measure BP(Gu et al., 2009) has been made. It can be said that there are at least 3 different recording setups how to equipp a bed with a PPG sensor.

The first type of recording setup is used by Wong and his colleagues (Wong et al., 2009; Gu et al., 2009; Wong et al., 2010) and it consits of two PPG sensors embedded into the mattress placed in a straight line under the patient’s back as seen on Figure 1.

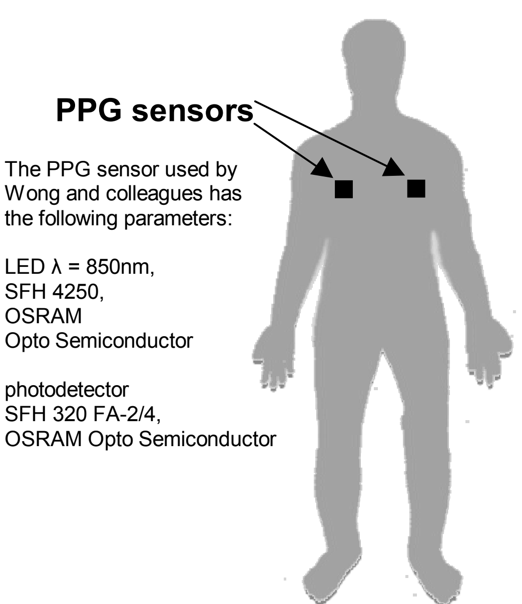

Figure 1. PPG recording setup by Wong and colleagues

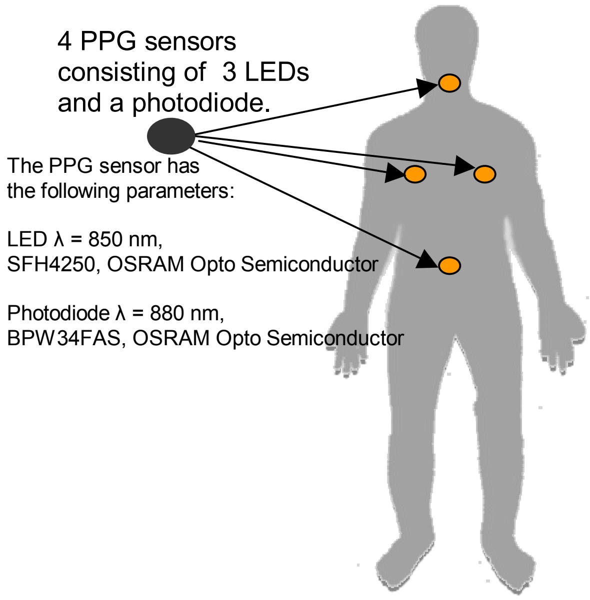

Figure 2. 4 PPG sensor layout

The second type of the recording setup consists of 4 PPG sensors distributed over the body area in a diamond like shape(Brüser et al, 2012). The distribution of the PPG sensors is seen in Figure 2. Inside the PPG sensor the LEDs emitt light into the mattress and the photodiode detects the changes of the backscattered light intensity. Body movements like respiration and cardiac vibrations change the geometry of the mattress and this changes the backscattered light intensity.

The third type of recording setup consits of one PPG sensor embedded into bed between coil springs(Maki et al., 2010). This data aquisition setup is seen in Figure 3.
This measurement setup consists of one PPG sensor placed in between the bed springs under the thorax area. All of the spring coils are covered with cloth and connected together. Inside the PPG sensor the LED emitts light into the mattress and the phototransistor detects the changes of the backscattered light intensity. Just like mentioned in the previous recording setup description, body movements like respiration and cardiac vibrations change the geometry of the mattress and this changes the backscattered light intensity.

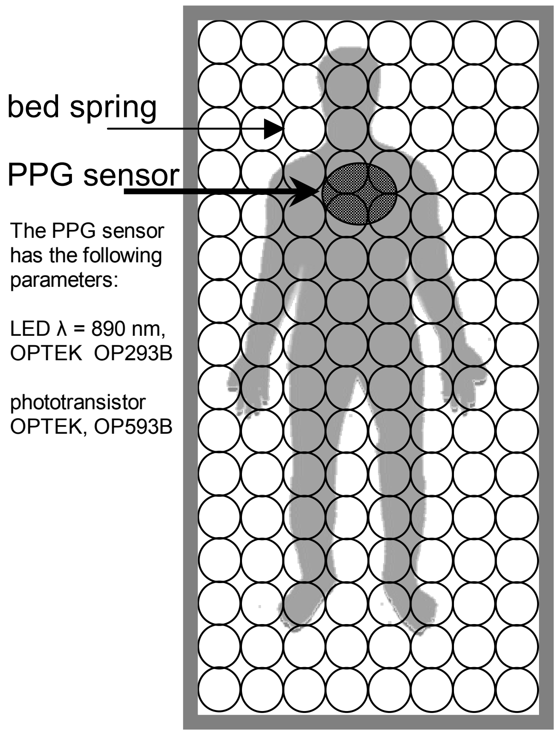

Figure 3. A setup there the PPG sensor is placed between the spring coils of the mattress.

Pillows

There are at least four electronically equipped PPG method based pillows, designed by Cha and his colleagues (Cha et al., 2008), Le and his colleagues (Lee et al., 2009), Singh and colleagues(Singh et al., 2014) and Yin and Muthukumar(Yin and Muthukumar, 2013).

Cha et al., 2008 proposed a PPG equipped pillow there the sensor was attached close to the neck area. The system consisted of the PPG sensor, current-to-voltage converter, high and lowpass filters and an amplifier.The PPG sensor consisted of one infrared LED, λ = 950 nm, and phototransistor which converted the changes of the light intensity into current. The current signal was converted to voltage and high pass filter was applied. The filtered signal was amplified and filtered with a low pass filter before it was digitized and fed to the computer. The setup of the pillow designed by Cha and his colleagues is seen in Figure 4.

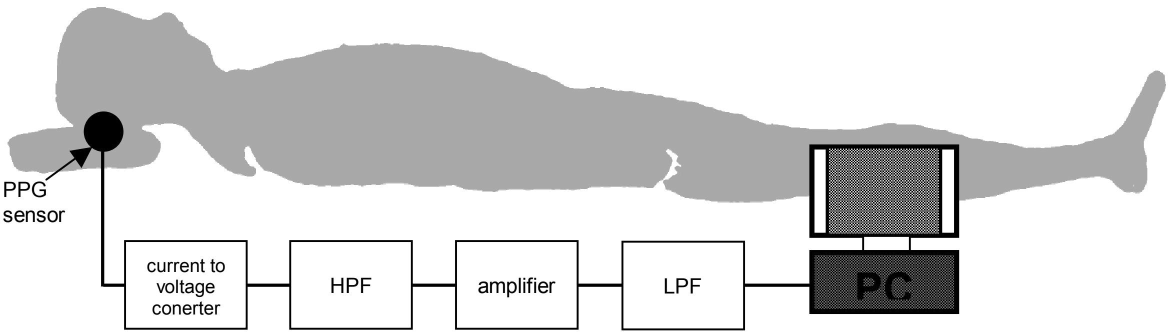

Figure 4. The principle of PPG method based pillow designed by Cha and colleagues.

Lee and colleagues (Lee et al., 2009) proposed a PPG method based electronic pillow which consisted of PPG sensor with 3 LEDs and one photodiode. In addition to PPG measurement, capacitive ECG electrodes were used. In rthis reflectance mode PPG sensor 3 LEDs were used, placed from each other 10 mm apart in a triangular shape. The detected signal was bandpassed with filters 0.15 Hz – 10 Hz for HR signal extraction and 0.13 Hz – 0.48 Hz for BR signal extraction. The system designed by Lee and colleagues is shown in Figure 5.

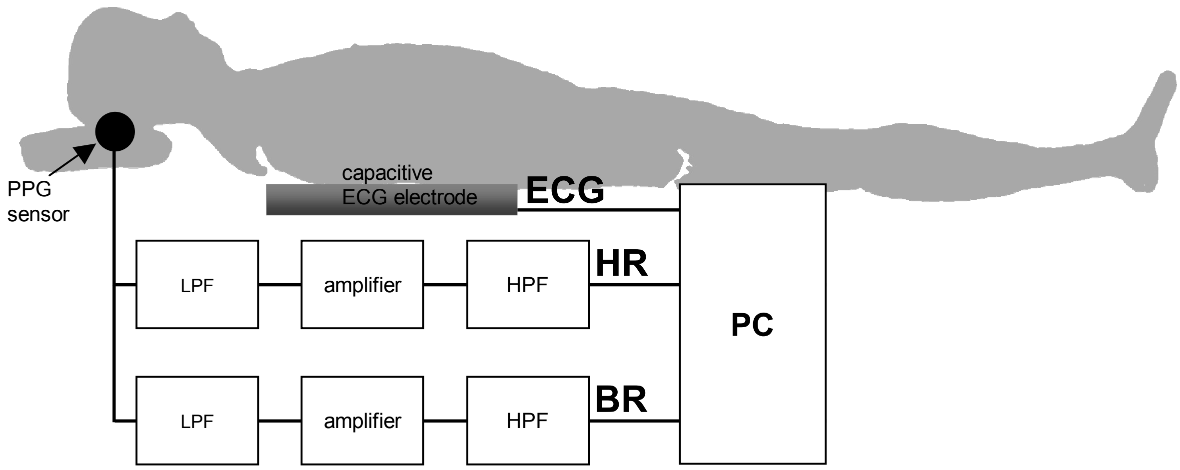

Figure 5. The principle of PPG method based pillow designed by Lee and colleagues

Yin and Muthukumar (Yin and Muthukumar, 2013) proposed a system there the LEDs and photodetectors were mounted inside the pillow. A very similiar pillow has been designed by Singh and colleagues (Singh et al., 2014).

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2.2.3 Fiber optic sensors based beds

measures

- body movements

design principle

- fiber optic cable

Fiber optic sensors usually consists of a light source, optical fiber, sensor and a detector. The following pages show that under certain circumstances the fiber optic cable can act as a sensor itself. The measurement principle is based on the fact that changes in the body movement modulate the bendings of the sensors and these changes can be detected as changes of optical loss.The following text desribes different usages of fiber optic sensors. In 2010 Nishiyama and colleagues (Nishiyama et al., 2010) designed a hetero core fiber optic based sensor system. The fiber optic cable was single mode with 9µm core diameter and the inserted sensors had 5µm diameter. Two different data aqusition devices were designed, data aquistion device with sensors in parallel and data aquistion device with sensors in successive order. The first device consisted of 8 sensors in parallel with sensors placed under the chest and abdomen area as seen in Figure 1. The second device consisted of 8 sensors in successive order as can be seen in Figure 2.

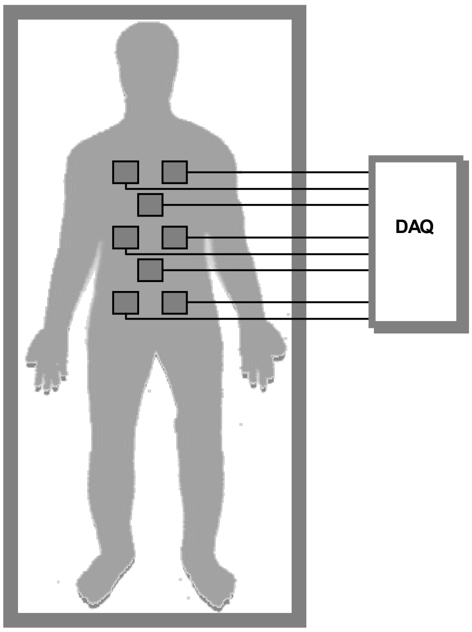

Figure 1. A parallel setup of 8 sensors by Nishiyama et al.

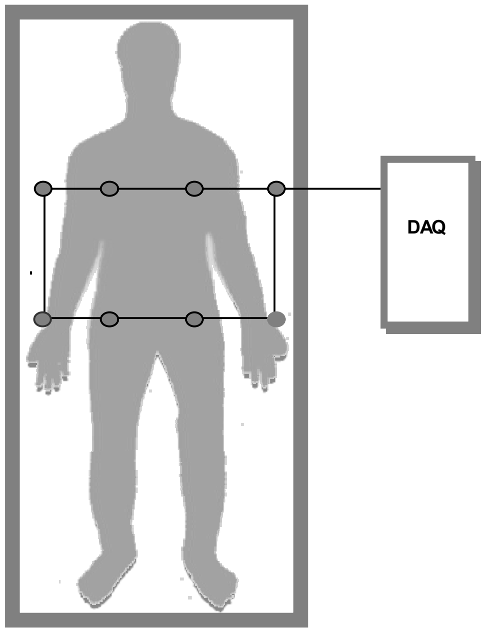

Figure 2. A setup of 8 sensors in an array by Nishiyama et al.

(Malakuti and Albu, 2010) designed a pressure measuring mattress consisting of 144 optical pressure sensors. The area there the sensors were placed was 3 x 8 inches grid. The measured sensors outputs were sampled at 5.3 Hz. Based on these signals, pressure distribution maps in the video(pattern) domain were generated. This means that the image seen is not a shape of a body but a rectangular matrix of cells based on the signal correlation analysis. In order to minimize the time and computational complexity required for the pressure map image signal processing, a similarity matrix is used. The similarity matrix is a sliding window with a size of 400 samples. Within each iteration the similarity matrix shifts 50 samples (9.5 seconds). The output of the signals is written into a text file, readable by all text viewers.

In 1992 Tamura and colleagues (Tamura et al., 1992) designed a pressure measurement bed based on the usage of three multmode step index fiber optic sensors placed under the neck, abdomen and knee area as seen on Figure 3. Many years later Walsh and colleagues (Walsh et al., 2011) designed a device named Under Mattesss Bed Sensor (UMBS). The origin of the mattress was a Tatex Controls Inc bed occupancy sensor, now expanded into a grid of 24 fiber optic pressure sensors having size of 1 x 90 x 23 cm. This UMBS sensor recording setup is seen in Figure 4.

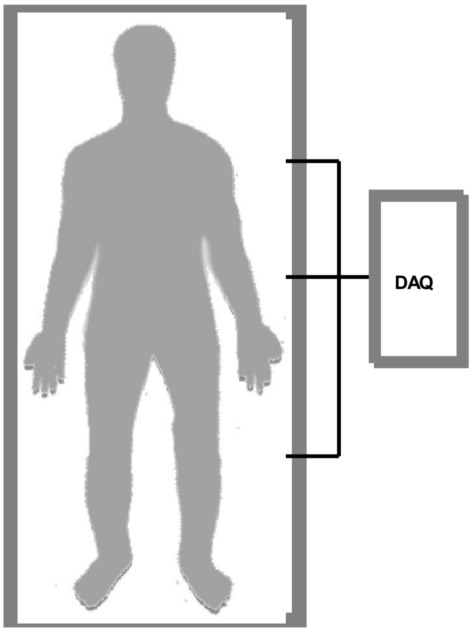

Figure 3. Multimode step index fiber optic senor recording by Tamura et al.

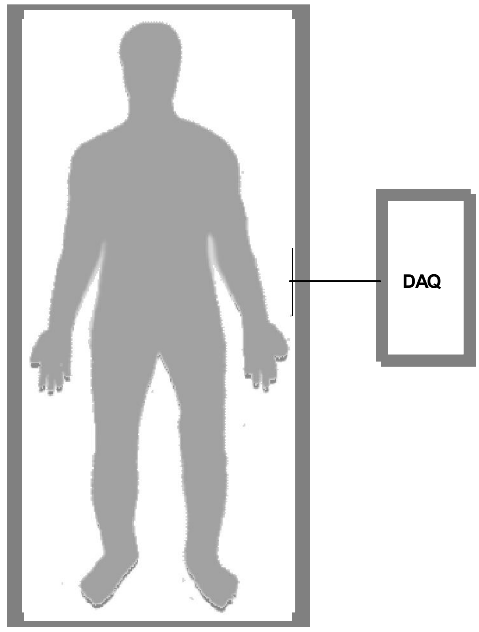

Figure 4. Under Mattress Bed Sensor (UMBS) by Walsh et al.

Podbreznik and colleagues (Podbreznik et al., 2013) designed a fiber optic speckle interferomer. The device consists of a 650 nm LED taken from the DVD device, plastic optical fiber and a linear optical sensor array. Detected signals are processed into 1 D signal by using phase shift transformation. The fiber optic cable layout was a “S” shape.

Spillman and colleagues (Spillman et al., 2004) designed a device with two different modal modulation techniques were used. The first tehnique based on Statistical Mode Sensing (STM) multimode optical fibre was excited by a coherent laser and the signal was detected with a digital camera. With the aid of this technique, a sum of absolute values of the change in light intensity is calculated. In the second technique, Higher Order Mode Excitation (HOME) only higher order modes are excited. Any change in the multimode optical fibre transposes the high order modes into low order modes, detected by a large area detector. The experiments showed that only HOME sensor was able to detect HR.

In 2008 Fook and colleagues (Fook et al., 2008) designed a Fiber Bragg Grating pressure sensor system.The sensor system consists of standard single mode telecomunication optical fiber cable and 12 sensors. The layout of the sensors is seen in Figure 5.

In 2009 Chen and colleagues have(Chen et al., 2009; Chen et al., 2011; Chen et al., 2014) designed a fiber optic sensor based pillow for HR monitoring. The pillow consists of multimode fiber, optical transmitter and reciever. Because the changes of HR induce body and head movement these changes modulate light intensity inside the fiber. The device can be seen in Figure 6.

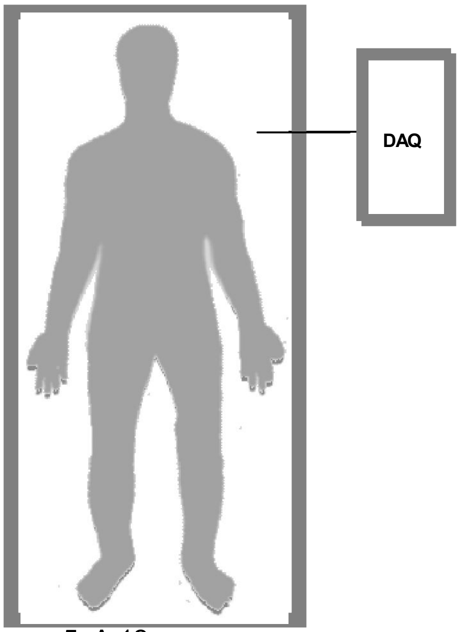

Figure 5. A 12 sensor array recording setup by Fook et al.

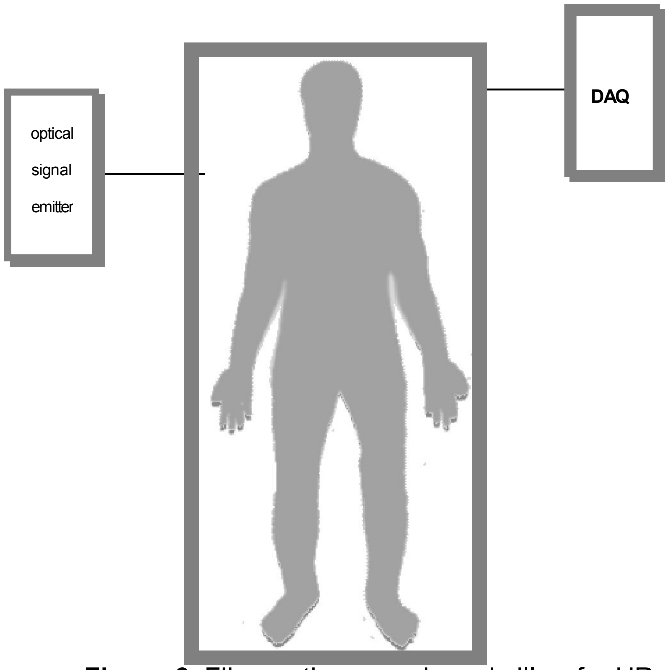

Figure 6. Fiber optic sensor based pillow for HR monitoring by Chen et al.

Townsend and colleagues (Townsend et al., 2012) created a pressure sensor array consisting of two plastic layers with dimensions 80 cm x 25 cm with 24 evenly spaced sensors in an array. The pressure distribution is shown as a color map in the [0 1] scale where maximum pressure is shown in white and minimal pressure is shown in black color.

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2.2.4 body's IR radiation measurement based beds

measures

- breathing rate
- OSA

design principle

- PIR
- cameras

Infrared radiation is radiation caused by the rotations and vibrations of the molecules. Considering the fact that temperature is a measure of average atomic kinetic energy, one can measure the temperature of the object in a non-contact way by measuring the object's radiation frequency band.In order to determine the total amount of energy emitted by the body (object), it has to be taken into account the limits of the spectra and find an integral withe the usage of the Stefan-Boltzmann Law:

$$\mathbf{R}_T = \int \boldsymbol{\varepsilon}_{\omega,T} d\omega = \sigma \mathbf{T}^4$$

Equation 1. The Stefan-Boltzmann Law.

Where: R the integral radiactvity
ε total power radiated per unit area
ω frequency spectra
σ the Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2K^4
T temperature in Kelvin

The infrared (IR) radiation has wavelength in the spectra of 700 nm to 1 mm and unvisible to the eye. The IR spectra is usually divided into 3 bands: near-infrared (NIR, 0.7μm - 3 μm), mid-infrared (MIR, 3μm- 50μm) and far-infrared(FIR, 50μm-1000μm). It has to be kept in mind that the limits of the bands vary from article to article very much. The placement of the IR radiation in the electromagnetic wave's spectrum is shown in Figure 1.

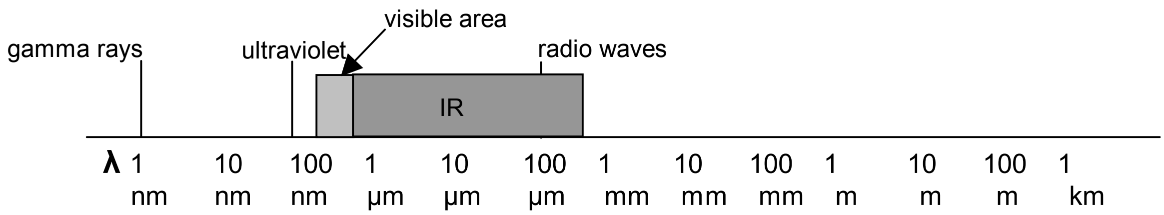

Figure 1. spectrum of electromagnetic waves

The types of IR measurement devices

Typically IR measurement devices are classified into 2 big classes: quantum detectors and thermal detectors.Quantum detectors work on the principle of photoeffect, meaning that when a photon strikes the sensor, a free electron is generated. Quantum detectors have low noise and fast response but require cryogenic cooling. Thermal detectors work on the principle of absorbing the thermal radiation. Thermal detectors are slower and not so sensitive but don't require cooling and therefore are easier to operate. Both classes of devices have sub-classes and there are review articles that describe it in more detail, for example (Rogalski, 2012) can be recomended because in addition to the classification of devices it also includes the history of the development of IR detectors.

Brief history of medical IR measurement

The first IR image of the human was taken in 1928(Szentkuti, Kavanagh and Grazio, 2011).The first usage of IR thermography in biomedicine was in 1952 in Germany where a bolometer was used for scanning the body and in 1956 a thermometer was used for detecting breast cancer(Szentkuti, Kavanagh and Grazio, 2011). More details about the usage of IR in medicine can be found from several biomedical engineering books or overview articles(Szentkuti, Kavanagh and Grazio, 2011;Hildebrandt ,Raschner and Ammer, 2010; Berz and Sauer, 2007).

The use of IR sensors in sleep medicine

The use of electronic devices for tracking the sleeping patient’s health status is a complicated task and therefore non-contact devices are prefered. The usage of IR sensors gives an opportunity to track temperature changes in a non-contact way and as it can be seen from the articles refered, in some cases it can be used for detecting apnea episodes. There are some difficulties because of the possibility the patient moves his/her body or covers the measurable area with a cloth.

2.2.4.1 non-video based methods: the usage of PIRs and thermopiles

PIR is a synonym of Passive Infra Red, a shortange used for describing motion detection sensors used primarly in security. It is very uncommon to use PIRs in medicine because usually PIRs have only relay output. Therefore, before continuing with the PIR based methods some PIR basics are given.The working principle of PIR is simple: it uses a dual element pyroelectric sensor in differential mode. When there is no movement, both elements detect the same amount of IR and there is no output. However, when there is somebody moving, one dual element detects IR in a different amount compared to the other element and therefore the sensor acts, producing voltage output. The sensor area is covered with plastic lens what protects the sensor and also shapes the alarm field of view coverage. Figures 2 and 3 show the outer and inner look of the PIR sensor.

Figure 2. the outer view of the PIR

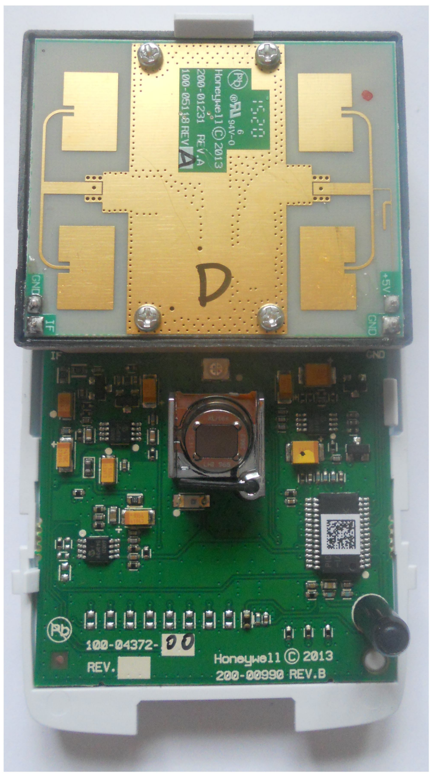

Figure 3. the inner view of the PIR

In 2013 Hers and colleagues (Hers et al., 2013) designed a system for detecting central apnea of the adults with PIR sensors. They did not want to measure respiratory rate. The system consists of 6 PIR sensors, placed in 3 groups of 2 PIRs in semi-circle above the patient's chest and the data was recorded with AVR microcontroller and SD card. Data was sampled @ 10 Hz, 10 points per second.They concluded that the closer the sensors are to the chest, the more they are sensitive to the patient's respiratorymovement. Also they found that the ideal sensor's distance from the patient is 20-50 cm. The setup of the PIRs is shown in Figure 4.

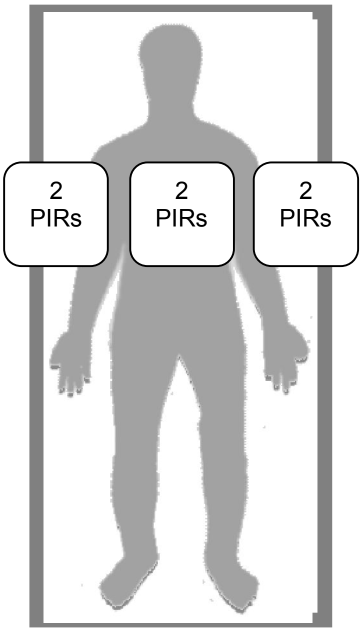

Figure 4. PIR setup by Hers et al., 2013

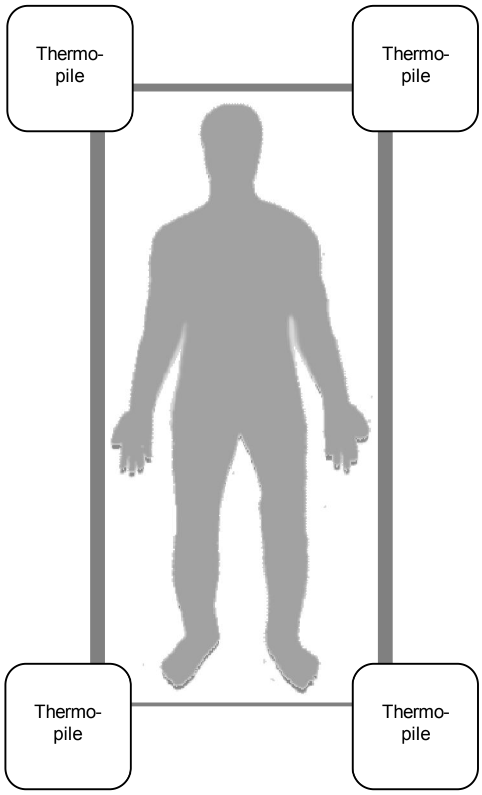

Figure 5. PIR setup by Shin et al., 2003

Thermopile based body movement detection method

In 2003 Shin and colleagues (Shin et al., 2003) designed a system what used 4 IR thermopile sensors placed in the corners of the bed. Adaptive neuro-fuzzy inference system ANFIS was used to classify signals into classes: head only, whole body and leg only movement.The setup is shown in Figure 5.

2.2.4.2 Camera based methods

There are very many articles describing the usage of different IR cameras for measuring chest movements.Things are more complicated when trying to measure air flow from the nose because the patient may cover the face area during sleep with the cloth. In spite of these difficulties IR cameras have been used for tracking the sleeping patient's nostril area(Murthy et al., 2009; Fei, Pavlidis and Murthy, 2009). In many articles Wang and colleagues have discussed about the IR image analysis in order to detect OSA from the IR images(video)(Wang & Hunter 2008; Wang, Ahmed and Hunter 2006 and Wang, Ahmed and Hunter 2007). IR video has been recorded with many different methods, including the usage of light sources.

IR video recording with the usage of light sources

In order to enchance the quality of the IR video recording sometimes light sources are used. The light sources may be lamps, LEDs or lasers. The usage of separate IR camera and IR light source for video monitoring makes the recording more flexible, specially when different light sources with different wavelengths are used. For example in one case(Bernal et al., 2014) the chest movements are detected based on the comparision of the light pattern generated by the illuminator and the light pattern detected by the camera. The existing video recording systems vary from simple 1 camera based(Kuo et al., 2010; Bernal et al., 2014) to complex many camera based ones(Bai et al., 2012; Terado and Fujiwara, 2005). Considering the fact that the patient's chest moves slowly, the video can be aquired with slow rate, 5 frames per second(Kuo et al., 2010; Bernal et al., 2014).

In 2012 Bai and colleagues (Bai et al., 2012) designed a IR sensor based breath detection system.The system's data aqusition part consists of an IR illuminator, 2 IR cameras and 1 IR reflector.The IR illuminator is placed in the heading of the bed, the IR reflector is placed close to the legs and the 2 IR cameras are placed on the sides of the bed. The IR cameras detect IR light generated by the IR illuminator and reflector and capture the image data in the form of (x,y) cordinate readings. Then the data is sent to the PC via Bluetooth link. The resolution of the IR cameras is 1024x768 pixels. The software of the system is written in C sharp and VB.NET. The setup of the system is described in Figure 6.

In 2005 Terado and Fujiwara (Terado and Fujiwara, 2005) designed a system what consists of 4 IR cameras placed on the corners of the bed and 2 luminous markers attached to the left and right sides of the subject's abdominal region. The luminous markers are small arrays of 16 IR LED diodes, placed in 4x4 matrix attached to the tape. The IR LED array has the dimensions of 10mmx10mm and the tape there the IR LED array is attached to has dimensions 16mm x 35 mm. The setup is shown in Figure 7.

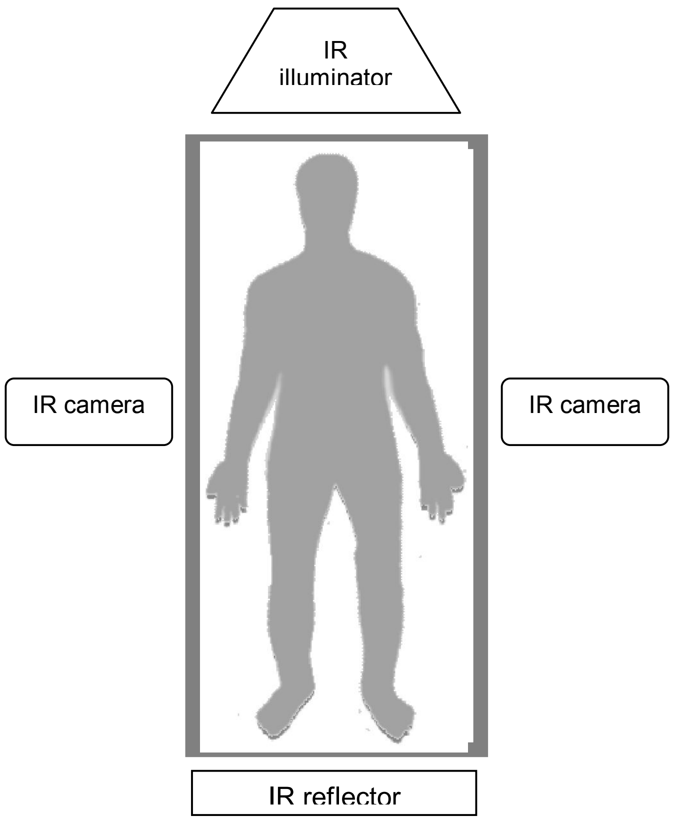

Figure 6. The IR recording setup by Bai et al, 2012.

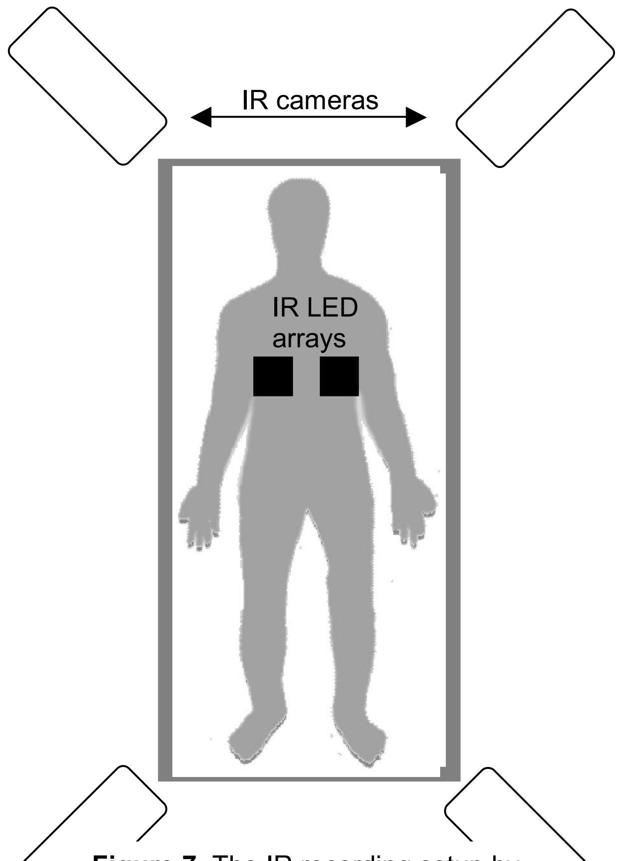

Figure 7. The IR recording setup by Terado and Fujiwara, 2005

IR video recording with the usage of light sources: the Kinect based approach

The Kinect is a Microsoft Xbox 360 video game console with built-in sensors: RGB camera, 4 microphones, accelerometer, IR projector and CMOS IR camera(Bethencourt and Jaulin, 2013). Because this game console is so easily applicable, scientists started to use it in their experiments and 2 examples about using Kinect IR camera are described here.

In 2012 Martinez and Stiefelhagen (Martinez and Stiefelhagen, 2012) designed a breath rate monitor what uses a fixed IR dot pattern, a IR camera. The IR camera, Kinect, has a resolution of 1280x1024 pizxels and records 9.1 frames per second. All dots are tracked for 30 seconds and the trajectories of the dots are fused together with Principal Component Analysis, PCA. Respiratory rate is detected with the usage of Autoregressive Spectral Analysis.

In 2013 Loblaw and colleagues (Loblaw et al., 2013) designed a system for monitoring sleeping patient's respiratory rate with using IR camera and Microsoft Kinect IR projector. The Kinect projector is used for generating approximately 30 000 IR dots and the motion of the dots is detected with the IR camera 2-nd order Butterworth filter, 0.1 Hz-1.5 Hz is used. Next moving Fourier transform is applied. The moving Fourier transform uses Hamming window with the length 512 samples and takes 6 samples between each transform. Backround subtraction algorithm is applied to the camera signal.

IR recording with CCD cameras

CCD means Charge Coupled Device, an electrical component what works similiar to shift register, shifting the detected charge between capacitive elements. The concept of the device is very old. For example Boyle's 1974 patent refers back to an article published in 1970(Boyle and Smith, 1974). Today CCD has been well used as a digital imaging sensor.

In 2004 Kuo and colleagues (Kuo et al., 2004) designed a system for capturing sleeping patient's body movement with IR night vision CCD (Charged Coupled Device) camera, TF-20M/IRB6. The camera was placed close to the head area or the bed. The image resolution is 640x480 pixels.The image data aquired is processed with a multi-layer feed-forward backpropagnation neural network. The software used is Microsoft Visual C++ and the Matrox Imaging Library (MIL).

In 2005 Aoki and colleagues (Aoki et al., 2005) designed a system for monitoring respiration(thorax movements) what uses a fiber grating (FG) projector and a CCD camera hanged above the bed. The FG projector what uses IR semiconductor laser @ 804 nm projects IR light spots on the thorax and then the CCD camera tracks the movements of the IR light spots 0.25 seconds per frame and the size of the image is 640x480.

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2.3 Eddy current measurement based electronic beds

2.3.1 Introduction

The eddy current measurement method is a method for measuring the changes of the body conductivity without electrodes. The method´s history dates back to 1851 when Foucault discovered eddy currents and therefore sometimes eddy currents are called Foucault currents(Kazimierczuk, 2014).When, in 1968 Tarjan and McFee conducted the first electrodeless impedance measurement for recording respiration and pulse signals(Geddes and Baker, 1989).

The measurement principle of the changes in the thorax conductivity contactlessly can be seen on Figure 1. In Figure 1, the coil generates primary magnetic field perpendicular to the current flow. This primary magnetic field induces eddy currents inside the chest and these eddy currents generate secondary magnetic field that can be detected with the same excitation coil or with a separate detection coil.

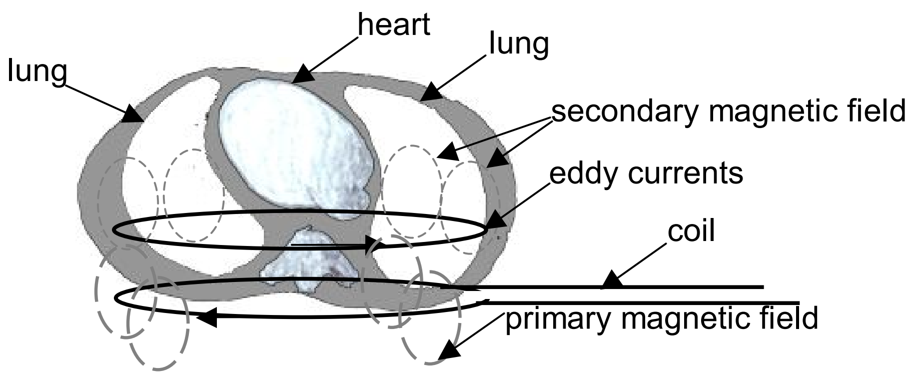

Figure 1. The generation of eddy currents inside the thorax

From the electronic point of view 2 different types of signal detection devices can be used: FM modulation based devices and AM modulation based devices. The more common FM modulation system uses Colpitts oscillator for creating time-varying magnetic field in the frequency range of 4 to 10 MHz. The signal measured from the body (re-induced magnetic field) is detected as the impedance change of the coil. The AM signal detection is based on the principle that the coil is part of the inductive potential divider and driven in constant frequency(Teichmann, 2010).

The eddy current measurement data aquistion method has found very little usage in the design of contacless sleep patient’s monitoring systems because of the following reasons: the signal is strongly affected by the ditstance from the coil, the signal is very sensitive to movement artefacts and the signal depends on the sensor geometry.Because the inductance changes of the body are small it is difficult to design sensitive and reliable pick-up electronics.

2.3.2 Eddy current measurement based electronic beds: existing methods and types

measures
- heart rate
- breathing rate
- lung volume

design principle
- the detection of changes of the body conductivity

In the design of electronically equipped beds based on eddy current detection single coil(Richter and Adler, 2005; Seeton and Adler, 2008) and multicoil(Mahdavi and Rosell-Ferrer, 2013; Steffen and Leonhardt, 2008) measurement methods have been used.
Adler and colleagues (Richter and Adler, 2005; Seeton and Adler, 2008) have been concentrating on the detection of a parameter that is correlated to HR and BR changes. This principle of action is reasonable because it is very difficult to measure conductivity distribution maps. In order to detect HR and BR silmoutanously with great accuracy, Steffen and Leonhardt (Steffen and Leonhardt, 2008) have designed a multicoil system based on 2 excitation and 3 detection coils.Mahdavi and Rosell-Ferrer (Mahdavi and Rosell-Ferrer, 2013) have done experiments with multicoil based measurement systems and found that the best results were obtained with semi-concentric and symmetric coil structure.In common practice the coil is a part of the oscillator and changes in coil inductance change the operating frequency of the coil.

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2.4 Capacitance measurement based electronic beds

2.4.1 Introduction

Measuring human body movements with capacitive sensors is a rather old technique. One of the earliest scientists ever to record human chest movements with capacitive sensors were Atzler and Lehmann who did their experiment in 1932(Atzler , E. and Lehmann, 1932). Atzler and Lehmann wanted to record heart activity with 2 condenser plates inserted into resonant circuit but during the recording they discovered that they had recorded respiration artefacts(Whitehorn and Perl, 1949).

During the first half of the 20th century chest movements were measured with 2 types of devices: ballistocardiographic beds and with capacitive sensors. The ballistocardiography was popular during 1930-1980s but the great interest in electromechanical detection of body movements started to fade in the 1970s because the devices were difficult to build: the electronic components were big and rigid, ballistocardiogrpahic beds were almost entirely mechanic and therefore the measured signals were heavily distorted(Cao et al., 2014).

During the 1970s scientists started to place the capacitor plates under the patient. This innovative idea opened the door for those types of beds what are described in the SCSB subchapter (2.5). The bed designed by Alihanka and colleagues in 1982 was named Static Charge Sensitive Bed but actually worked as a huge 2-plate capacitor(Alihanka et al., 1982). The reason why beds using capacitive effect for body movement detection were not popular before 1990s-2000s was technological: electronic components were still quite big and sensor materials were rigid and hard to cut.Metal plates were the only possible electrode materials but were rigid. In order to detect signals what are strong enough the metal plates had to be very big. This approach gave a lot of information about the fact that the patient has moved but very little about anything specific. Therefore the scientists started to search for new approach and the results were the usage of e-textiles, flexible sensors and the idea that the human body can be seen as one plate of the condenser.

Capacitive sensors used for measuring chest movements were named differently decades ago and these names are not very common any more. For example the devices were named: cardiokymograph (Vas et al., 1980), displacement cardiograph (Vas et al., 1980), proximity transducer (D.Groom, L.H. Medina and Y.T.Shivonen, 1964) and it causes a lot of confusion.

2.4.2 Main measurement methods

measure
- HR
- BR
- Body position
- Posture changes

design principles
- oscillation counting
- AC bridge
- charge time

The capacitance can be measured in many different ways. However, during the writing of this book it become evident that there are 3 capacitance measurement methods what have been used more often and these methods are described in brief here. These methods are the oscillation counting method, the usage of the AC bridge and the charge time method. For those who are interested in depth understanding of these methods the author recommends to read Robert B. Northrop's "Introduction to Instrumentation and Measurements", CRC Press, Taylor and Francis Group, 2005. Also Geddes and Baker's book about biomedical instrumentation can be recommended(Geddes and Baker, 1989).

oscillation counting method

This method consits of an oscillator circuit what generates time-varying square wave signal and the capacitance being measured is defined with the number of oscillations counted. This method has one specific property-namely, this method is digital in nature. Depending on the situation this can be a good or a bad result.

AC bridge

AC bridges consists of the AC signal source, balance detector and 4 arms: Z1, Z2, Z3 and Z4. The AC bridge circuit is presented on Figure 1. The arms are complex impedances. Then the bridge is in balance the potential difference between points A and B is zero and the detector D shows nothing. However, any disbalance causes a voltage drop and creates a signal having magnitude and phase. Mathematically it is shown in Equation 1 :

$$Z1 / Z2 = Z3 / Z4$$

Equation 1.
The balance between the arms.

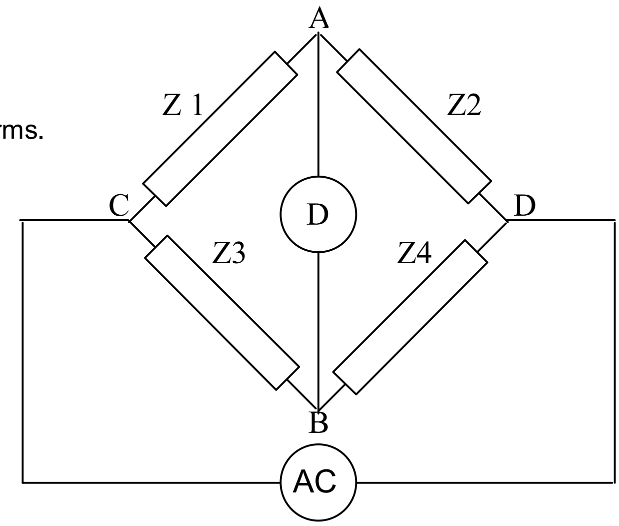

Figure 1. The AC bridge circuit.

Any one of the 4 complex impedances Z1, Z2, Z3 or Z4 could be unknown and therefore determined by the ratio of other three known ones. The AC bridge can be realized in a such a way that the unknown arm of the bridge is the capacitance sensor and therefore the bridge can be used for detecting capacitance changes. The reader has to know that there are many different types of bridges and although the use of the AC bridge might be benefital, building a AC bridge requires a lot of backround knowledge because the AC bridges are inherintly difficult and it takes some time to find out the best suitable bridge circuit.

Charge time method

This method takes the usage of the math what describes the capacitor charging process. The capacitor charges and discharges according to the exponent function and this also means that the capacitor charging-discharging is a time-dependant process. The charging process is described by Equation 2:

$$V(t) = V_0 \, (1- e^{-t/\tau})$$

Equation 2. The capacitance discharging process equation where:

V_0 intial voltage applied to the capacitor
t time
τ time constant

The capacitance measurement with capacitive electrodes placed in the bed can be done in many different ways. The following picture (Figure. 2) describes the most common data aquisition method used. It consists of sensing electrodes and at least one grounding electrode, often called Driven Right Leg electrode and the electronics circuitry. The Driven Right Leg electrode is used for reducing noise but because of the complexity of the circuitry, it is described in detail in a specific sub-chapter, 2.4.4. The electronics circuitry mostly consists of at least one amplifier, high pass filter, 50 Hz hum filter, low pass filter and analog-to-digital converter. The amplifiers used are operational amplifiers or instrumental amplifiers with very high input impedance.

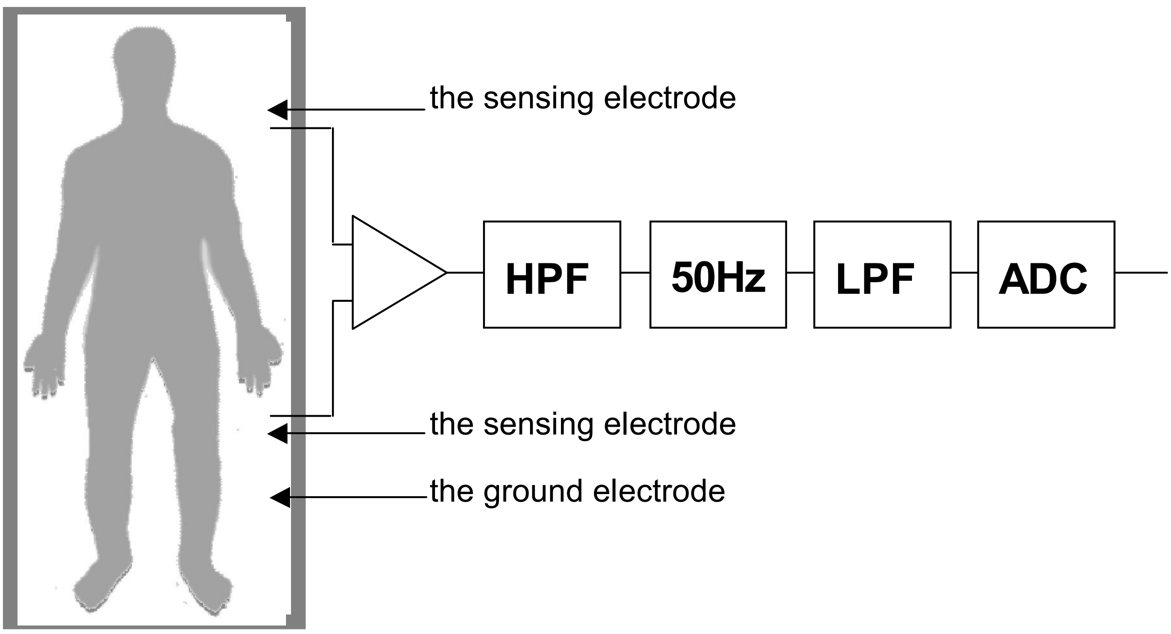

Figure 2. The typical capacitance measurement setup.

2.4.3 Sensor electrode placements

Among capacitive electrode measurements there has always been a lot of experimenting with the placement of the electrodes. The electrodes have been placed mainly under the head and legs(Ishijama,1993; Devot et al., 2007) and thorax area(Wu and Zhang,2008; Lee et al., 2009; Ito et al., 2013). The following pages describe 4 different approaches how to design capacitive electrode based measurement system.

Case 1

In an article published in 2013 Ito and colleagues (Ito et al., 2013) designed a measurement system what consisted of 6 conductive fabric belts acting as electrodes, having 3 proximity detection electrodes and 3 ECG electrodes. In order to detect the proximities of upper and lower body separately two sets of capacitance meters were used. One proximity detecting conductive fabric belt was placed under the thorax, one under the legs and one under the abdomen area. The ECG electrodes were placed in parallel to the proximity detection electrodes in the same places and the placement of the electrodes is seen in Figure 3.All the signals were digitized with 16 bit resolution ADC at 1kHz.In order to detect the proximities of upper and lower body separately 2 identical circuits were designed what consisted of an astabile multivibrator and frequency-to-voltage converter (National Semiconductor, LM231). The ECG measurement unit consisted of 2 high input impedance (10 TΩ, 2 pF) operational amplifiers (Texas Instruments, OPA134) acting as buffers, an instrumentation amplifier, power line filter and 2 inverting amplifiers.

Case 2

In 2007 Lim and colleagues (Lim et al., 2007) designed a non-contact ECG measurement system what consisted of 8 sensing electrodes placed under the thorax area of the body and one big electrode, the ground electrode made of conductive textile, under the legs. The sensing electrodes are active electrodes consisting of an high input impedance operational amplifier(OPA124, TI), resistor, electrode face and outer shielding. The size of the sensing electrode is 4 x 4 cm and the height is 12 mm.Each sensing electrode was connected to separate filter and amplifier unit and the output's of these pre-processed signals were digitized with NI DAQPad-6015 at 16 bit / 500 Hz sampling rate. Finally the signals were digitally filtered with LPF @ 40 Hz. The system is described in Figure 4.

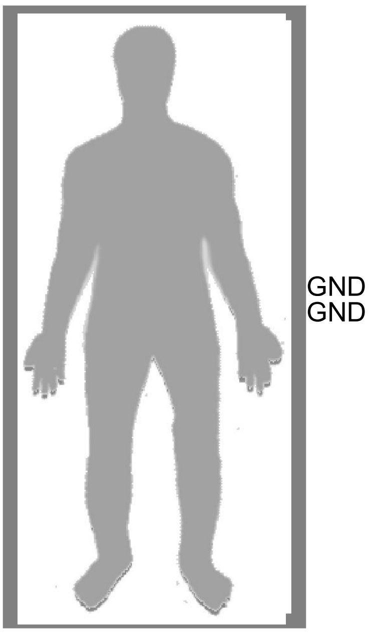

Figure 3. A system by Ito et al., 2013

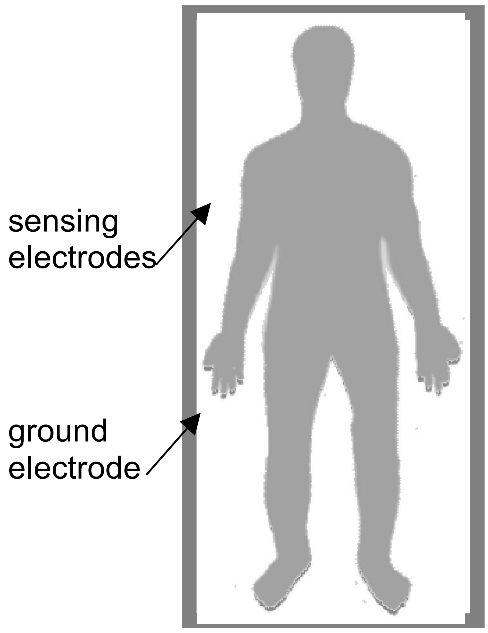

Figure 4. A system by Lim et al., 2007

Case 3

In 2008 J.H Oum and colleagues (J.H.Oum et al., 2008) designed a sensor for recording heart an breathing activity capacitevely with Colpitts oscillator. The device is based on the idea that cardiorespiratory movements modulate the frequency of the Colpitts oscillator and the change of the capacitance of the resonator represents the detected modulated signal. The signal of interest is detected after demodulating the oscillating signal.The sensor consists of 4 patch electrodes having sizes of 3cm x 3cm and placed 6 cm apart from each other.The layout of the patches is seen on Figure 5.

Case 4

In 2010 Eilebrecht and colleagues (Eilebrecht et al., 2010) designed a 9 electrode based capacitive ECG measurement system what consisted of the sensor unit, DAQ and PC. Although this system was meant to be a diagnostic tool used in ambulanse/intensive care, it can be used in the design of electronically equipped sensing mattressess as well. The 9 electrodes were placed in a 3 x 3 matrix (see Figure 6) where the 8 rounding electrodes were used as sensor electrodes and the center electrode as a driven ground electrode. The authors claim that this electrode placement makes it possible to record Einthoven and Goldberger lead signals.

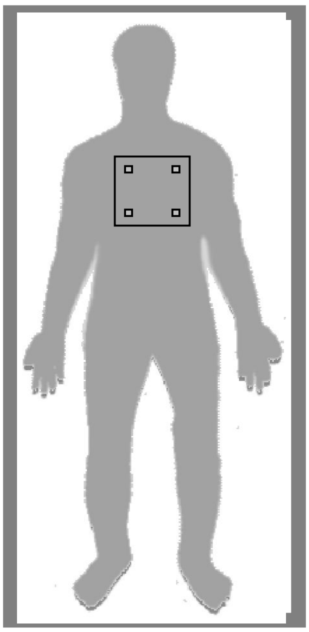

Figure 5. A system by Oum et al., 2008

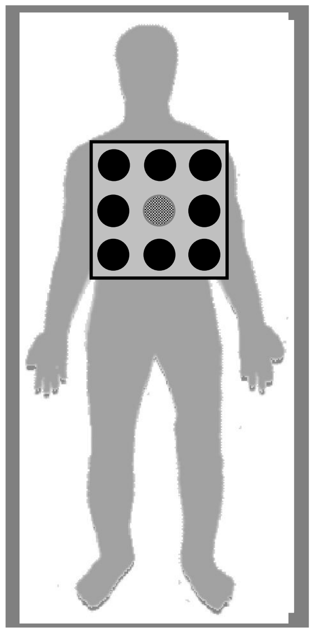

Figure 6. A system by Eilebrecht et al., 2010

On Figures 5 and 6 the sensors are placed on top of the patient because otherwise the placement of the sensing electrodes would be obscured by the chest. Also, the drawings are not to scale because otherwise it would be too difficult to notice.

Some capacitive electrode placements

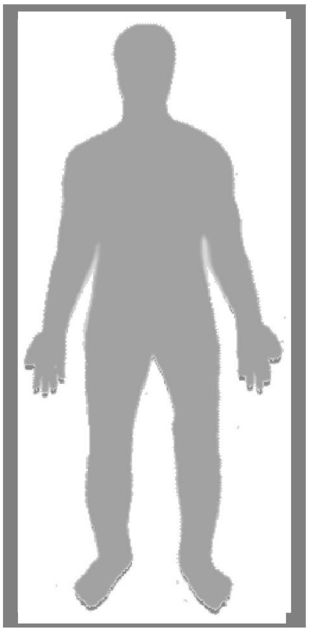

Figure 7. A system by Ishijama, 1993

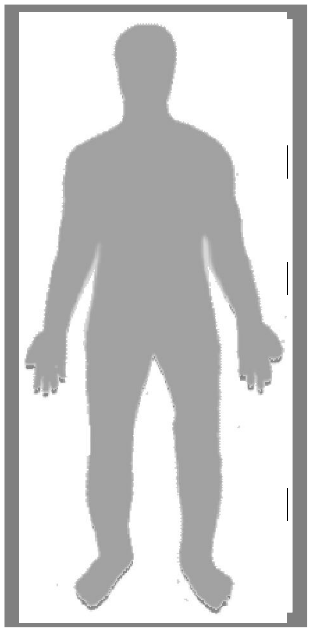

Figure 8. A system by Cheng et al., 2008

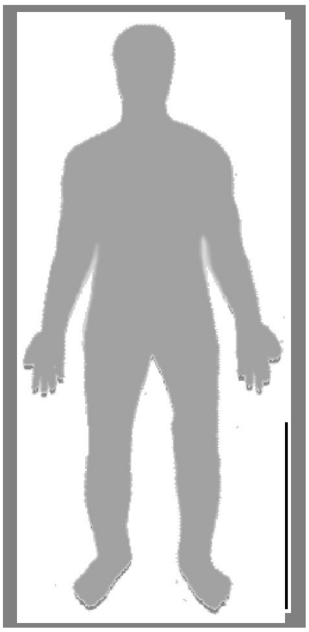

Figure 9. A system by Yi and Park, 2002

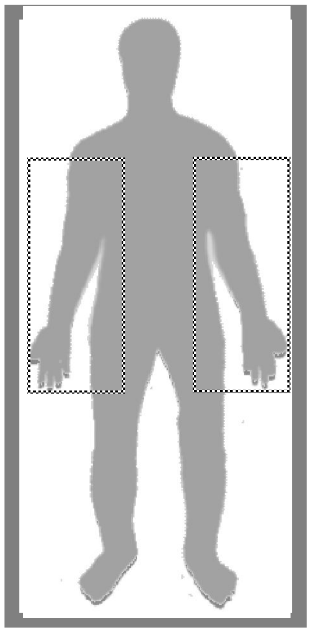

Figure 10. A system by Park et al., 2008

2.4.4 The Driven Right Leg concept

Electric signals originating from the human body are weak and suspectible to interference, movement artefacts and noise and this has to be taken into consideration of the design of biopotential amplifiers.
Possible sources of noise and interference are body movements, other electrical devices connected to the patient, power lines and nearby magnetic fields. These sources of noise and interference affect signal quality very much. In order to surpress these noises and interferences many different things can be done: shielding the device, twisting the electrodes, surrounding the patient and the measurement device with the Farady cage, apply notch filters or use differential recordings. All of these methods have their own pro's and con's and the choice of the method to be used depends on the situation. Describing all of these methods in detail would take very much space therefore only one method- driven right leg is described.

Very often noise and interference is present in all channels, therefore it can be called common signal. This common noise and interference signal is hard to surpress with filters but it can be very easily eliminated when the differential signal of the electrodes is recorded because then the noise common to all channels cancels out. This can be easily done with instrumentation amplifiers (INA). The instrumentation amplifier is an amplifier made of at least 2 amplifiers what amplifies the differential signal. The most common type of instrumentation amplifier is made of 3 amplifiers and it is seen in Figure 11.

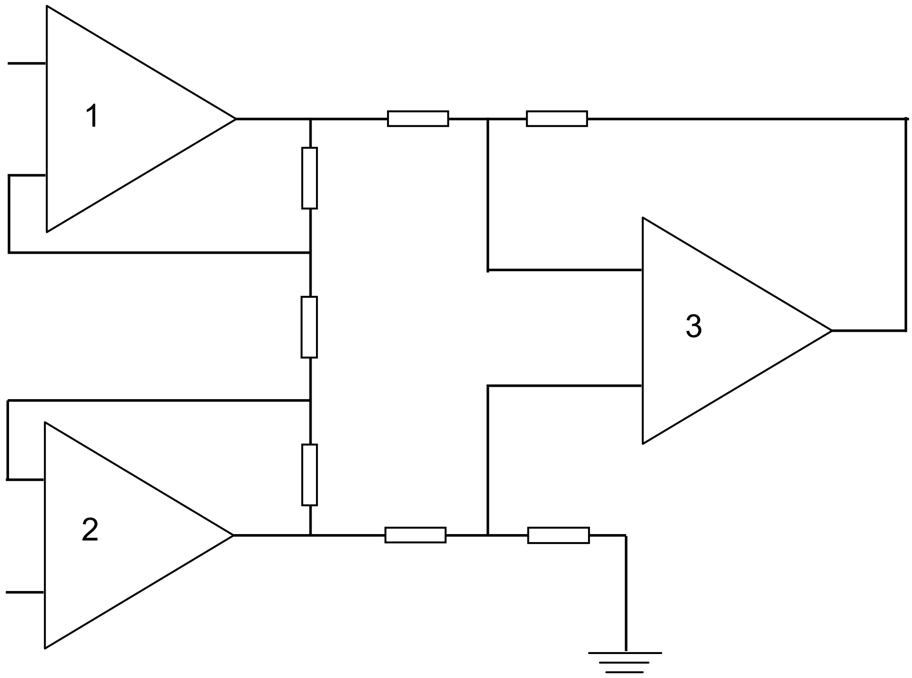

Figure 11. A typical 3 amplifier based instrumentation amplifier.

A typical 3 amplifier based instrumentation amplifier, just like the one seen in Figure 11. consists of 2 stages: the first stage made of amplifiers 1 and 2 and the second stage made of amplifier 3. The first stage is needed because it offers very high input. The second stage is needed because it amplifies the differential signal of the inputs conditioned by the amplifiers 1 and 2.

Although INA is a good device for recording biopotentials, still very much can be done in order to improve the signal quality. Possibly the most effective way to increase CMRR and therefore also signal quality is to use an electrode with negative feedback for surpressing common mode signal. Figure 12 shows a typical INA what is advanced with the addition of Driven Right Leg circuit.

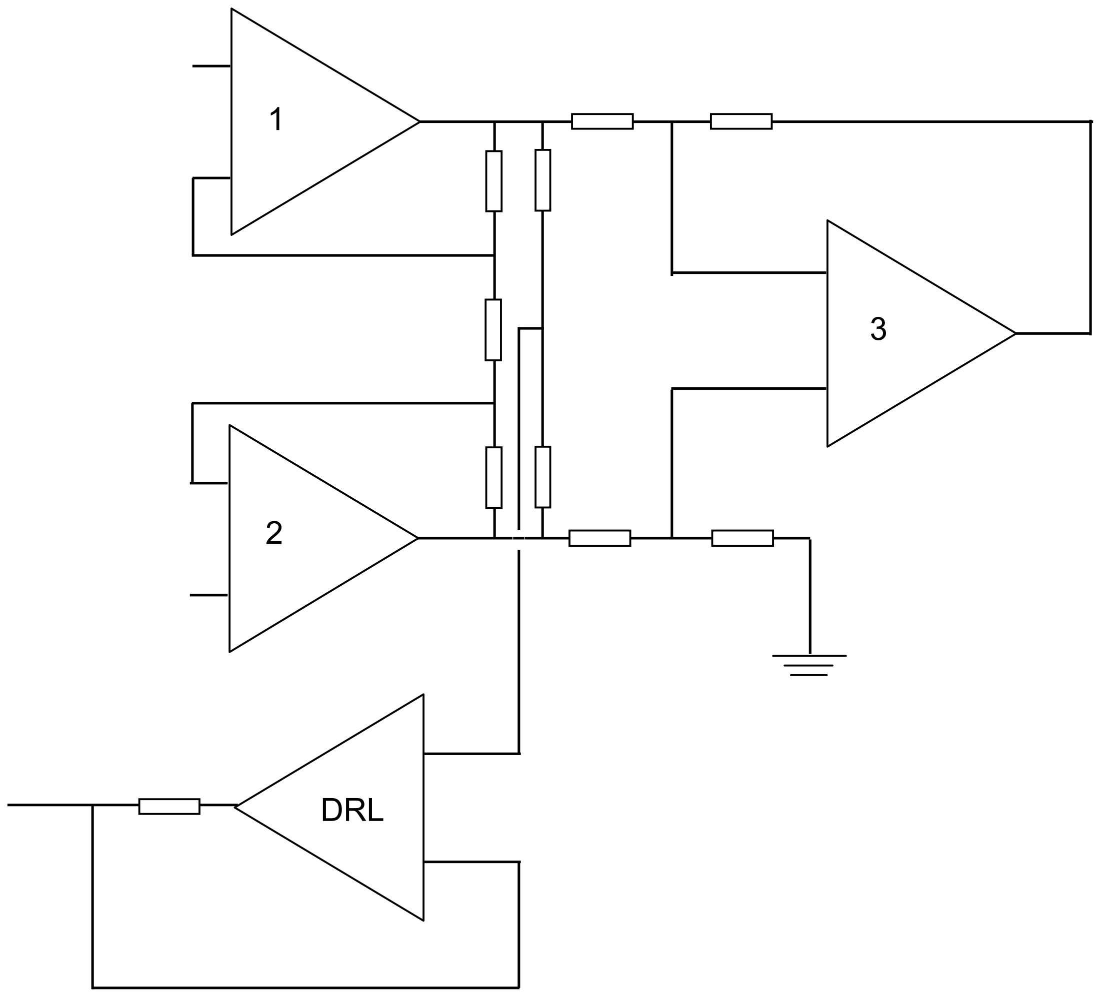

Figure 12. The instrumentation amplifier with Driven Right Leg circuit

The additional circuit is named Driven Right Leg because electrode connected to this circuit is connected to the patient's right leg. This helps to increase the signal tens of decibels.

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2.5 Static charge measurement based electronic beds

2.5.1 Introduction

2.5.2 Static charge measurement based electronic beds:existing methods and types

2.5.1 Introduction

The electric charge is a fundamental property of the elementary particle and has been described in huge amounts of publications and experiments for long time. This sub-chapter describes the usage of measuring static charges generated by friction. The following 3 examples shown in 2.5.2 describe how the body movements generate static charges on the measurement mattress and how these charges are converted into useful signal.

Typically charges are measured with electrostatic voltmeters and charge amplifiers. These 3 examples shown here use different electronic circuitry but the focus is on the usage of charge amplifiers. The charge amplifiers convert the charge into voltage. The process is based on the usage of Equation 1:

$$Q = V / C$$

Equation 1. The charge, and it's relation to the of voltage and capacitance where:

V voltage
C capacitance

Those who are interested in the details I would recommend Webster's "The measurement, instrumentation and sensors handbook" chapters 44(about charge measurement) and 45(about capacitance measurement) (Webster, 1999).Static charge measurement method is able to detect heart and breathing rate and body movements and posture changes but also has 2 disadvantages. Firstly, because of the high measurement sensitivity the mattress records movements generated by people moving nearby. Secondly, this method is not able to differentiate between different movement localisations.

2.5.2 Static charge measurement based electronic beds:existing methods and types

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measure
- HR
- BR
- body movements

design principles
- triboelctric effects

The static charge measurement based electronic beds have found very little usage in sleep medicine. The most commonly used charge measurement based bed is the one designed by Alihanka and colleagues, named as the Static Charge Sensitive Bed, SCSB. This sub-chapter describes 3 similiar patents describing the recording of BCG with mattresses what detect static electric charges generated by body movements(Hanna, 1976; Alihanka et al., 1982; Friesen et al., 1984). All of these 3 devices described later in more detail use 2 big metal plates separated with an insulator as sensing electrodes but the signal generation mechanism is different.

The patent filed by Hanna in 1975 (Hanna, 1976)describes a sensing device what uses a carrier signal in order to generate electric field on the senor's upper metal sheet. The patent filed by Alihanka and colleagues(Alihanka et al., 1982) in 1980 describes how the measurable electric charge is generated by the friction and rubbing between 2 materials with different dielectric constants what form the active layer of the mattress and how the potential difference between 2 sensing metal plates is measured.The patent filed by Friesen and colleagues(Friesen et al., 1984) in 1982 descrbies the measurememt of potential differences between charges of the human body and the sensor.

Static Charge Sensitive Bed (SCSB) by Alihanka and colleagues

The working principle of the mattress detecting static electric charges (Static Charge Sensitive Bed , SCSB) designed by Alihanka, Vaahtoranta and Björkqvist in 1980(Alihanka et al., 1982) is an advancement of one design patented earlier in 1977(Finnish Pat. No. 55113). The device works as follows.

Human body movements are detected by an active layer. The active layer consists of 2 materials with different dielectric constants and so any body movements cause the friction and rubbing between these materials and therefore generates electrical charges(Alihanka et al., 1981; Alihanka et al., 1982).These charges induce potential differences between two large metal plates what are placed under the active layer and separated from each other with an insulator plate. The metal plates have dimensions 200 cm x 90 cm x 0.1 mm and the potential differences are detected with differential AC or DC amplifier(Alihanka et al., 1981).In order to remove possible ambient artefacts the whole sensor system is covered with conductive and flexible outer shielding material(Alihanka et al., 1981; Alihanka et al., 1982). The whole measurement sensor, consisting of the active layer, metal plates, insulating plate and outer shielding is about 2 cm thick and weighs about 5 kg(Alihanka et al., 1981). The working principle of the device is seen in Figure 1.

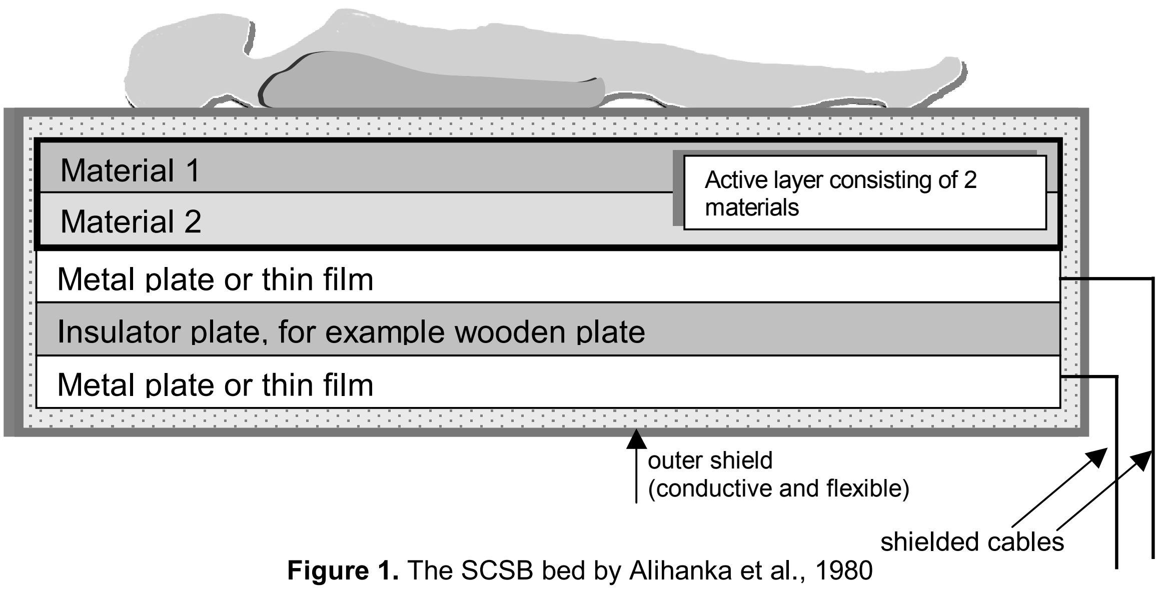

Figure 1. The SCSB bed by Alihanka et al., 1980

The signals recorded with SCSB are best explained in 2 earliest articles(Alihanka and Vahtoranta, 1979; Alihanka et al., 1981). The SCSB system has 2 drawbacks, first, because of the high measurement sensitivity the mattress records movements of people moving nearby (Alihanka and Vahtoranta, 1979) and secondly, the SCSB is not able to differentiate between different movement localisations(Rauhala et al., 1996).

The device designed by Harry Allen Hanna

In 1975 Hanna filed a patent describing a static charge measurement bed(Hanna, 1976). The device works as following.
The mattress consists of two conductive sheets or foils separated from each other with an insulating material and having upper and lower covers (see Figure 2).A carrier signal circuit is used to create electric field on the upper conductive sheet or foil and the lowersheet or foil acts as an electrical shield.Human body movements alter the electrical field generated by the carrier signal and this alteration can be detected as the impedance variation. This carrier modulated impedance variation signal is demodulated, amplified and sent out.

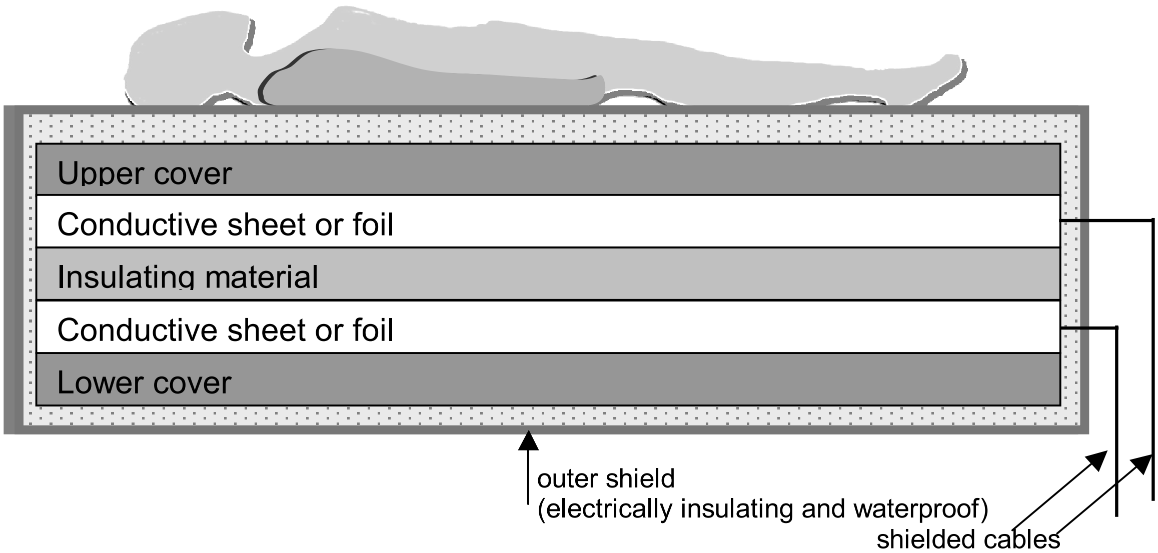

Figure 2. The device designed by Hanna, 1975.

The device designed by Friesen and colleagues

The sensor hardware construction designed by Friesen(Friesen et al., 1984) looks similiar to the one designed by Hanna(Hanna, 1976) but the measurement method is different. The sensor hardware consists of two conductive layers separated from each other with an insulating material (for example plastic) and upper and lower plastic covers. In order to provide better sealings the conductive layers are made a little bit smaller than the plastic layers. Also, the author proposed an alternate solution there the conductive layers are separeted from each other not with the plastic layer but with sufficiently big air gap.
Whereas Hanna used “active” sensing by creating the necessary electric field with the help of the carrier signal, Friesen’s patent uses “passive” sensing, based on the assumption that all physical bodies bear a net charge and therefore any body movement induces potential differences on the sensor layers(conductive layers). The generated potential differences are then amplified and conditioned with 3 high input impedance CMOS operational amplifiers.

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2.6 Pressure measurement based electronic beds

2.6.1 Introduction

Pressure measurement is the oldest and the most wide-spread data aquistion method used among electronically equipped beds. The roots of pressure measurement in the electronically equipped bed design lay in ballistocardiograpgy, a method first described by J.W.Gordon in 1877(Inan et al., 2015). BCG focused on the measurement of heartbeat induced body center of mass changes and within decades faded because the measurement instrumentation was complicated and the signal was easily affected by body movements. However, in sleep medicine the main focus is on moni-toring respiration and sometimes also heart rate and from this point of view, the BCG measurement instrumentation can be very simple.

With decades new sensors and sensor materials have been developed and today there is no need for building extra beds for measurements. New pressure measurement sensors are small and flexible and can be placed under the mattress. With the aid of flexible sensors and electronics smart mattresses what measure heart rate, breathing rate, body movements and pressure image can be made.

Today there are two schools of thought in sleep medicine who use pressure measurement in the electronic bed design: the one who records primarly heart and respiratory rate and the one who monitors health status and behavior.For heart rate and breathing rate measurements usually flexible under-the-mattress type sensors are used. In order to monitor health status, behavior, sleep and wake pattern, the sensor does not have to be very complicated and therefore some very simple and robust pressure measurement methods, like load cells, are used.

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2.6.2 Load cells

measures
- heart rate
- breathing rate
- body movements
- sleep-wake pattern

design principle
- resistance measurement with Wheatstone bridge

Load cells are strain gauge sensors what have been in use for long time. The popularity of the load cells can be explained by it's simplicity in design and in usage. Typically load cells are used for measuring large, static or slowly changing forces(Webster, 1999).

The main principle of action is the fact that the resistance of the load cell changes in accordance to the force applied to it. The load cells are in different sizes and shapes, usually made of aminium or stainless steel. In terms of electrical conditioning, 1, 2 or 4 element varying Wheatstone bridge circuit is used.

In sleep medicine load cells have found little usage, having been placed under the 4 corners of the bed for measuring body movements(Schrempf et al., 2010; Austin et al., 2012), ballistocardiography(Lee et al., 2016) or breathing rate(Zachary et al., 2009). Also, it is interesting to mention that load cells have been used for detecting sleep-wake activity pattern(Adami et al., 2010). Considering the fact that people weight so little, any type of load cells can be used but best results can be attained with the usage of piezoceramic load cells because their output voltage starts from zero voltage(Kurihara, 2011).

The frequency range of load cell collected signal is very low because usually human voluntary movements stay in the range of 3 Hz – 4 Hz(Adami et al., 2005). Although the signal frequency is low and in limited range, the main problem with the load cell data aquistion is the lack of clear frequency spectrum of the detected signal(Chung et al., 2007).

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2.6.3 Force sensitive resistors

measures

- heart rate
- breathing rate
- body movements
- sleep-wake pattern

design principle

- resistance measurement

Force Sensing Resistors, FSR, are polymer thick film sensors with resistance decreasing with the increasing force applied. It is important to notice that FSR sensors may have a variation of 15%-29% in resistance. FSR have small hysteresis and have little sensitivity to vibration and heat(Webster, 1999). Figure 1 describes the working principle of the FSR.

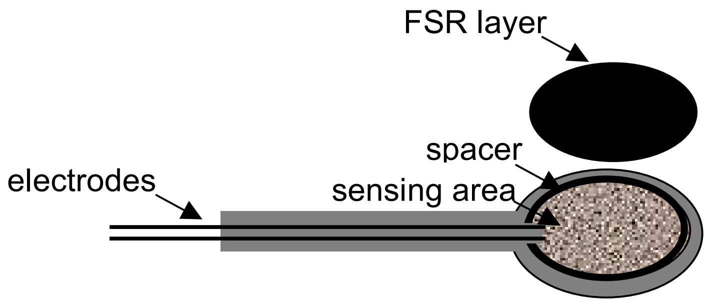

Figure 1. The structure of the typical FSR sensor.

Force is applied to the FSR layer. The more force is applied, the more the FSR layer comes into contact with the sensing area. The FSR layer and the sensing area are separated from each other with a spacer.

Force sensitive resistors(FSR) can be small in size and flexible. This offers many oppurtunities to use them as sensors embedded into mattress for monitoring breathing(Harada et al., 2000; Lokavee et al., 2012; Pino et al., 2013; H.F.M van Der Loos, 2003; H.F.M van Der Loos, 2001), stay in bed(Gaddam et al., 2008; Gaddam, 2010), pressure ulcer(Ostadabbas et al., 2011; Yousefi et al., 2011); posture classification(Boughorbel et al., 2012; Hsia C.C et al., 2009; Yousefi at al., 2011) and bed ergonomics(Hsu and Lo, 2013) aspects. Also FSR enable breathing rate(Lokavee et al., 2012) measurement and if needed, even pressure distribution map can be made(Yousefi at al., 2011 ; Hsu and Lo, 2013).

Breathing measurement with FSR

In order to detect sleeping patient's breathing FSRs have been embedded into mattresses(H.F.M van Der Loos, 2003; H.F.M van Der Loos, 2001 ; Lokavee et al., 2012; Pino et al., 2013) and pillows(Harada et al., 2000; Lokavee et al., 2012). These sensors have been used in the matrix layout being placed under the pillow(Harada et al., 2000) or all over the bed(H.F.M van Der Loos, 2003; H.F.M van Der Loos, 2001 ; Pino et al., 2013).

In the following, 3 different approaches using FSR sensors in matrix layout for breathing rate measurement are described, all of them using 24+ FSR sensors. However, one should still remeber that the resistances of the sensors vary very much. Even so much that Interlink Electronics FSR manual warns:"FSRs are not suitable for precision measurements".

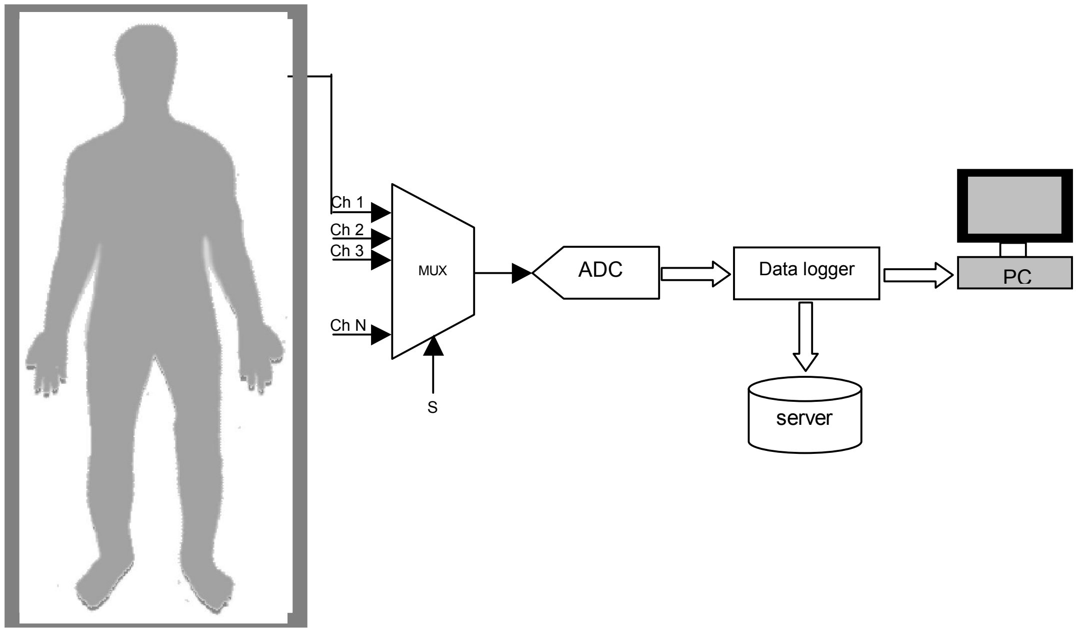

Figure 2. A typical use of FSR sensors in matrix layout

Case 1

In 1998 Van der Loos and colleagues (Kobayashi et al., 1998) started SleepSmart project with aiming to develop a smart mattress what could detect posture changes, temperature variation, HR and BR. In Nov.10, 2000, H.F.Machiel Van der Loos, Joel S.Ford, Hisato Kobayashi, Joseph Norman and Tomoaki Osada recieved a patent no: US 6,468,234, Sleepsmart. In 2001 Van der Loos and colleagues (H.F.M van Der Loos, 2001) wrote an article describing exactly how 54 RTDs and 54 FSRs were used for detecting HR, BR, body positions and body surface temperature. Within this design FSRs and RTDs were placed under the torso and legs with adjusting sensors in the thorax area more closer to each other(10cm) than in the legs area(20cm). HR was measured with a resolution of 0.5 beats per minute within a 5 second data set and BR was measured after every 5 seconds within 25 second data set. In an article written in 2003(H.F.M van Der Loos, 2003), Van der Loos and colleagues describe the Sleepsmart bed more thoroughly and argues how to integrate multisensor mattress with a parallel bed project, "Morpheus" what is a mattress actuation system.

Case 2

In 2000 Harada et al designed a FSR sensor based pillow.The pillow consists of 28 FSR sensors placed on the plastic board with dimensions of 230 x 375 mm. The FSR sensors were placed 50 mm crosswise and 60 mm lengthwise and covered with 11.2 mm wide and 5.1 mm tall rubber. The respiration detection algorithm is based on the following criteria.First, absolute values of the sensors signals are calculated based on the difference of the current and former signal. Secondly, summing up all sensor's absolute values of difference—the total change of pressure data is gathered.Finally, one respiration event is considered as two peaks of total change of pressure data. The tests with one 22 year old female and one 21 year old male showed that the pillow does not accurately count respirations during posture changes and head movements.

Case 3

In 2013 Pino and colleagues (Pino et al., 2013) designed a FSR sensor based pressure measurement system for sleep investigations. The aim of the project was to detect body movement,apnea, respiratory rate(RR) and RR variability. In order to realize it, 24 FSR sensors with the sensor's active area 38.1 x 38.1 mm were aligned in 3 rows and 8 columns in a bed, under the thorax area. The total sensing area of the device is 300 x 900 mm. Three 8-channel analog multiplexers and a ATMega64 microcontroller were used for the data aquisition . Because the sampling frequency of the ADC was 250 Hz per channel and each channel sampled 8 sensors, the final sampling rate of the sensors was 32,9 Hz. After that data was sent via serial port to the Logomatic v2 data logger and saved in a microSD card. In order to detect respiratory signal accurately, a automatic channel algorithm was implemented—based on the body position, the best respiratory channel was selected.

Body posture classification

Case 1

(Boughorbel et al., 2012) did reasearch finding the optimum number of sensors, positions and sizes for posture classification. The search included the following types of classifiers: linear, quadratic, nearest neighbourhood and SVM. The tests done with21 subjects, 4 sleeping postures and 3 minutes in each posture resulted that the optimum number of sensors is 40, aligned in 4 x 10 sensor layout having distance of 6 cm between the sensors and an offset of 20 cm from the head side.

Case 2

(Hsia C.C. et al., 2009) described 2 different FSR sensor based mattresses and signal processing algorithms for detecting the body posture.The first, 16 sensor layout mattress was used for determing the cost-effectivness of the sensing mattress and 56 sensor layout for determing the effectivness of posture detection.Two different types of FSR sensors from Interlink Electronics were used: circle-shape part no. 402 and trimmable strip shape part no. 408. In 16 sensor based setup the 16 strip shape sensors were placed under the thorax area only. In the 56 sensor layout circular shape sensors aligned in matrix layout were placed under the thorax area and strip shaped under the lower body. The data was aquired with 1 Hz sampling rate.Data obtained from the 56 sensor layout system was processed and evaluated with the following methods: kurtosis, skewness, PCA, descriptive statistics and SVM classification. After testing 8 subjects 3 times in the left and right yearner, left and right foetus, log and supine positions, 5 minutes in each position two conclusions were made. First, as it can be expected, the result is highly dependent of the size, shape and density of the sensors. Secondly, the 16 sensor layout can detect 3 postures but only then there are small movements.

Case 3

In order to track sleeping patient's body movements, specially body posture changes, (Yousefi at al., 2011) designed a smart mattress consisting of 2048 FSR sensors and signal processing unit, applying Principal Component Analysis (PCA) and Indipendent Component Analysis (ICA). The 2048 FSR sensors were placed in 32 x 64 sensor layout and each sensor is able to measure pressure in the range of 0 – 100 mmHg.The signal sampling rate was 0.6 Hz. Based on this data, pressure distribution images were created and the data went throuh 3 stages of classification: normalization, Eigenspace Projection, and K Nearest Neighbour kNN. The system and algorithm was evaluated by 6 subjects in 5 postures: supine, left foetus, right foetus, left yearner, right yearner and concluded that the PCA based approach predicts patient's posture with 97.7% average accuracy.

Stay in bed and sleep-wake pattern monitoring

Quite often sleep researchers are interested in heart and breathing rate measurements and forget the biological and behavioral aspects. While heart rate and breathing rate measurements give directlty sleep related data, the biological and behavioral aspects give data what has it's value in long-term use. The monitoring of the patient's sleeping habbits gives a lot of backround information what can be used during the diagnosis phase. Even so, when the patient has strange sleeping habbits, a sudden change in it gives a lot of information. This approach can find a lot of usage among those who have serious sleep or other health problems or those who need constant monitoring in the hospital.

Gaddam and colleagues have taken this approach under serious consideration and written many articles about it(Gaddam et alt., 2008, 2009, 2010). Their articles are based on using 4 FSR sensors being placed under the bedposts. This is similiar to the use of load cells(see sub-chapter 2.6.2).Here is an example, Case 1.

Case 1

In 2009 (Gaddam et al., 2009) designed a home monitoring system for the elderly. In this design, the four Tekscan's FlexiForce FSR sensors placed under the bedposts detect the patient's presence and position in the bed. The outputs from the sensors were sent to Silabs C8051F020 microcontroller's 12-bit ADC. Signals from the microcontrolller are sent wirelessly with the Radiomatrix 433 MHz transmitter to the monitoring station. The signal conditioning is done with switched capacitor voltage inverter MAX828 and with a LPF in order to suppress invereter's output noise at 12 kHz. The reference voltage of the microcontroller's built-in ADC is 2.4V. Microcontroller's digital I/O ports are used for interfacing with the LCD. In order to test the each sensors output the surface area of the experimental setup table was divided into 10 cells in width and 14 cells in length. A 6 kg fixed weight was placed on each corner of the bed. Based on these measurements the table was calibrated and divided into 4 zones with each zone corresponding to one bedpost's sensor output.

Special case: The electronic mattress ergonomics aspect

Considering the huge importance of the mattress's ergonomics to the sleeping person, (Hsu and Lo, 2013) designed a system there actuators, covered with FSR sensors on the top were used for creating pressure distribution images and based on this data change the mattress support to the body. The system consists of 9 x 18 sensor-actuator elements. The sensors are Uneo GS25-100N FSR sensors developed by UCCTW Co and the actuators were A43F4AB-24-001 linear speed 100 mm per second. The system was run by Friendly ARM Mini 2440 single board computer with software written in C++.

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2.6.4 Electromechanic film

measures

- heart rate
- breathing rate
- body movements

design principle

- charge measurement

The electromechanical film, EMF, material was invented by Kari Kirjavainen in 1987 (US patent 4,654,546; Mar. 31, 1987) and developed by the Technical Research Center of Finland in 1987(Alametsä, 2004).According to Paajanen (Paajanen et al., 2000):

"The ElectroMechanical Film (EMFi) is a thin, cellular, biaxially oriented polypropylene film that can be used as an electret".

The EMF consists of an polypropylene film, charged with corona discharge method and coated with electrically conductive electrode layers(Rajala and Lekkala, 2010). Changes of pressure acting on the surface generate charges and so the EMF sensor acts like an active capacitor.Typically EMF film sensor is 65-70 µm thick but for example the EMF S-series film itself is 65 µm thick (EMFIT Film Specifications, Rev C, 17.3.2003) and aluminium or silver surface electrodes are 9 µm – 20 µm thick (EMFIT S-series sensors specifications, Rev C. 1.5.2003; EMFIT L-series sensors specifications, Rev C. 1.3.2003). Protective layers might be for example 100 µm thick(EMFIT S-series sensors specifications, Rev C. 1.5.2003).The general structure of the EMF sensor is given in Figure 1.

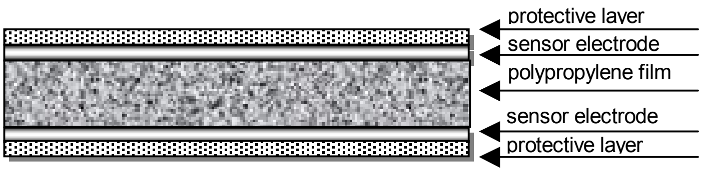

Figure 1. The structure of the EMF sensor sheet.

The capacitance of the 70 µm EMF film is 14 pF / cm^2 and the piezoelectric coefficent is 170 pC / N (Rajala and Lekkala, 2010). A problem with EMF sensor film is aging because EMF sensor film's piezoelectric transducer coefficent starts to decrease permanently at 50 °C (Alametsä et al., 2004). According to Brüser and colleagues,(Brüser et al., 2012) the EMF sensor sensitivity decreases within months of usage.The EMF film sensor is sensitive to forces applied normal to the surface area only(Rajala and Lekkala, 2010). For comaprision, PVDF sensor is 5 times less sensitive to forces applied normal to the surface of the sensor area but on the other hand PVDF is sensitive to forces acting in length and width also(Rajala and Lekkala, 2010).

Among the many articles about the usage of EMF sensors there are 3 interesting cases to be studied. The most advantageous system is described in Case 1 where the focus is on healthcare and connection to local area networks. Case 2 is focused on signal processing. Case 3 shows that good results in heart rate and breathing rate measurement can be achived even with the usage of one, big enough, EMF sensor what is placed under the thorax area.

Case 1 : The Emfit SafeBed

This is the most complete and complex usage of the EMF sensors in sleep medicine.Emfit Ltd has developed a bed sensor and system called Networked SafeBed. This system uses EMF sensor unit placed under the bed mattress (as seen in Figure. 2) and LAN for communicating with nurses. The sensing device uses thin-film ferroelectret sensor L-4060SL for detecting HR and BR changes, movement activity, fall and epileptic seizures. Patient health status data is networked to (W)LAN or Ethernet. The system also uses nurse call buttons and alarms delivered to DECT phones. The software equipped with the device is Windows compatible and data is stored into Microsoft SQL database. However MS SQL Server software is not included.

(Networked (IP) Nurse-Call System with Passive Patient Monitoring user manual, Emfit SafeBed IP / DVM2008 SW System Main Technical Details, www.emfit.com)

Case 2 : The matrix layout of EMF sensors

This is another very interesting case because here are many EMF sensors used in matrix layout. The detected signals are processed with complex algorithms. The hardware of the system is simple, using 160 EMF sensors placed on 1m x 2m area, using Texas Instruments switched integrator amplifier IC DDC 112 (Kortelainen and Virkkala, 2007). For the sensor's placement see Figure 3.

Case 3 : The simultaneous usage of EMF and PPG sensors

This is a case there the EMF sensor is used silmutaneously with PPG sensors. The PPG sensor layout of the system is described earlier, in sub-chapter 2.2.2, page 14, Figure 2. The system uses only one 30 cm x 60 cm EMF sensor placed under the thorax area and sampled at 200 Hz. The researchers discovered EMF sensor's decrease in sensitivity over many months of usage(Brüser et al., 2012).

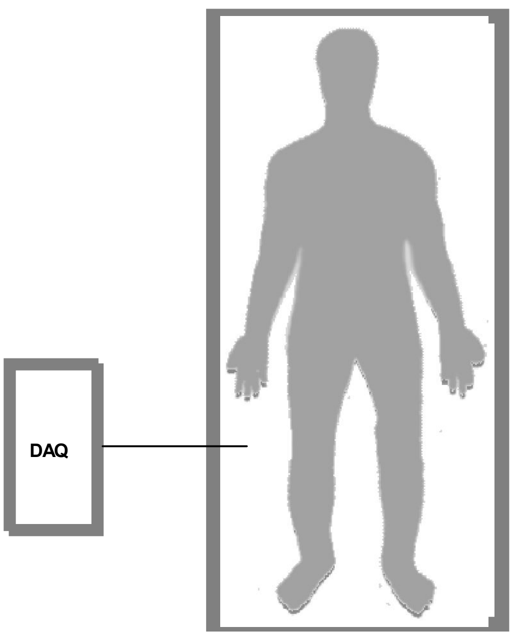

Figure 2. The Emfit SafeBed sensor placement

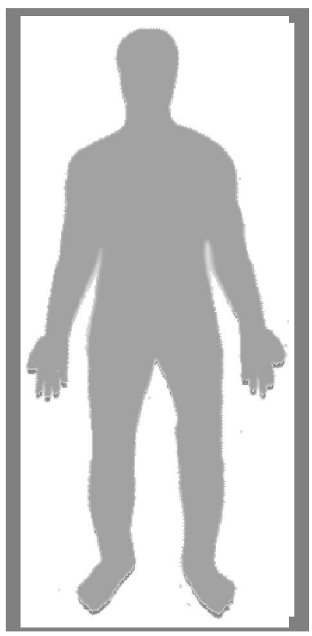

Figure 3. The EMF matrix sensor placement by Kortelainen and Virkkala, 2007

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2.6.5 Polyvinylidenefluoride aka PVDF

measures
- heart rate
- breathing rate
- body movements

design principle
- charge measurement

The polyvinylidenefluoride (PVDF) is a fluoropolymer with very high piezo activity found by Kawai in 1969. Typically PVDF piezo films have thickness in the range of 9-110 µm, capacitance 380 pF / cm^2 @ 1 kHz(for 32 µm thick), Young's modulus 2-4 x 10^9 N / m^2 and temperature range – 40 ºC to 80 ºC(Piezo Film SensorsTechnical Manual,Measurement Specialties, Inc.P/N 1005663-1 REV B 02 APR 99). The electrodes are usually made of Cu-Ni or Silver ink(Metallized Piezo Film Sheets, data sheet,Metallized Piezo Film Rev 1 www.meas-spec.com 05/12/2009).Because of the fact that the PVDF generates voltage output based on the temporal differential properites, PVDF measures only dynamic changes of pressure(Wang et al., 2003).

As it can be seen from the literature, 5 different types of PVDF BCG sensors have been developed: 2 different layouts of the single sensor(Wang et al., 2003; Wang et al., 2012), 2 different multisensor layouts(Hwang et al., 2013; Jung et al., 2014; Park et al., 2014; Guerrero et al., 2013; Brüser et al., 2015) and one combined sensor(Jiang et al., 2010). Although each type of sensor has it's own pro's and con's, the ultimate result is that a multisensor system, however strange it is, is always better than a single sensor system.

The one-sensor systems.

Case 1: The one sheet approach

In 2003 Wang and colleagues (Wang et al., 2003) designed a single PVDF sensor system, consisting of the PVDF film with the measurements 140 mm x 200 mm, a JFET operation amplifier based charge amplifier and 50 Hz notch filter. The sensor was placed on the bed, under the thorax area and the measured signals were sampled at 100 Hz. In order to detect HR and RR, wavelet signal processing was applied.

Case 2: The S-shape approach

In 2012 Wang and colleagues (Wang et al., 2012) designed a PVDF based heart and lung activity measurement sensor by placing a PVDF cable on the measurable area in the S-shape way, just like seen in Figure 1.The sensor cable conisisted of a 30 µm PVDF material coated with 4µm copper electrodes from both sides. The detected signal was first amplified with a charge amplifier, filtered with 4-th order LPF(25 Hz) and extracted into heart and lung activity signals with fourth order low and band pass filters: the heart activity was extracted with 0.7 Hz-1.5 Hz bandpass filter and lung activity was extracted with a 0.5 Hz low pass filter. Butterworth flters were used because of the linear relation between phase shift and it affects the frequency only slightly. The system is powered with 5 V DC and consumes current 32 mA.

The multiple sensor systems.

Case 1: The 4 sensor approach

The 4 sensor approach is based on the idea by Hwang and colleagues who used 4 PVDF sensors placed in parallel to each other onto a layer. The PVDF sensors had measurements 26 cm x 4 cm and there was a 3 cm separation between the sensors(Hwang et al., 2014; Jung et al., 2014). The signal was extracted into heart and lung activities with PCA (principal component analysis), segmented and compared to adaptive threshold levels. Although the sensor consisted of 4 arrays, only 2 arrays measuring abdomen movements were used(Hwang et al., 2014). The sensor layout is shown in Figure 2.

Case 2: The 8 sensor approach

The 8 sensor approach is based on the works by Gurrero and Brüser and colleagues. The 8 sensors with having measurements 19 mm x 171 mm x 52 µm were placed in 2 columns so that they covered area 64 cm x 64 cm. The sensors were placed on a mat having measurements 72 cm x 100 cm and placed under the bed mattress. The signals were sampled at 50 Hz(Brüser et al., 2015;Guerrero et al., 2013).

In 2015 Brüser and colleagues (Brüser et al., 2015) compared single and multichannel BCG signals aquired with PVDF sensors. In order to do it, signals aquired with 8 channel mattress were compared to the virtual single channel what was a sum of these 8 channels. After comparing 28 overnight recordings processed with different methods, the result was that multichannel recording is much better.

The combined sensor system

In 2010 Jiang and colleagues (Jiang et al., 2010) developed a cardiorespiratory sensor made of 2 different sensors, movement sensitive sensor for recording respiratory movements and movement insensitive sensor for recording heart activity. The design consisted of a flexible substrate to which PVDF sensors were placed. The PVDF sensor coated with flexible is considered as the bending insensitive heart activity measuring sensor.

PVDF sensor placements

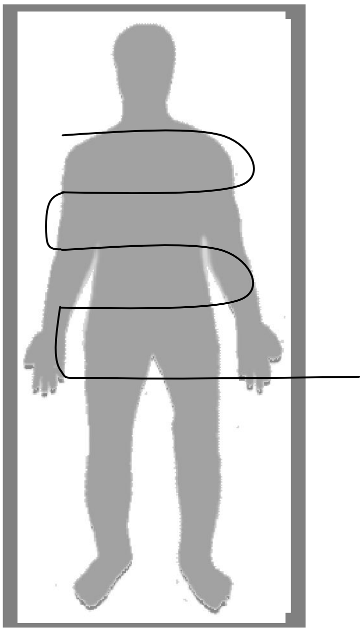

Figure 1. The S-shape sensor by Wang et al., 2012

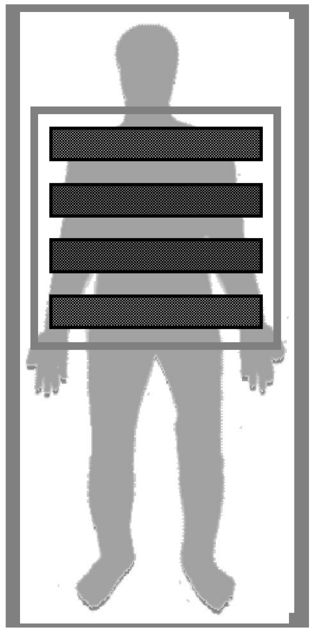

Figure 2. The 4 sensor system by Hwang and Jung et al., 2014

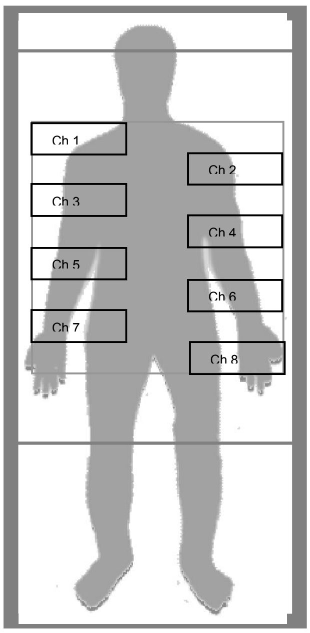

Figure 3. The 8 sensor system by Gurrero and Brüser et al., 2013

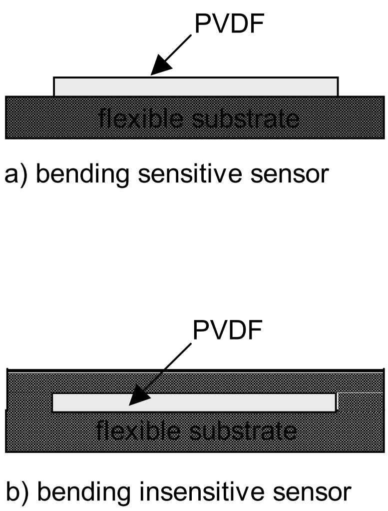

Figure 4. The combined sensor by Jiang et al., 2010

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2.6.6 Air mattresses

measures
- heart rate
- breathing rate
- body movements

design principle
- pressure measurement

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There are many articles describing the usage of air mattresses or cushions as sensors for cardiorespiratory signal measurement in sleep medicine. Basically these articles can be devided into two: systems using a single air mattress/cushion as a sensor and systems using many. Also, there is one interesting measurement system what combines single air cushion sensor's output with ultrasound sensor's output(Hata et al., 2007).

The popularity of the air mattress/cushion based measurement systems can be explained with the ease of build and usage. However, these systems also have disadvantages. The user has to be careful not causing any leakage to the mattress or the tube connecting it to the electronics circuitry. This can be a problem when the air tubes are long and there is a lot of activity going around. The following sub-chapter is divided into 2 sections, describing single and multiple air compartment based measurement systems.

Single air compartment based measurement systems

There are many different articles describing the usage of single mattress as a sensor and while going into details, 2 different sensor setups can be seen. There is one setup, used by most of the researchers where one single air mattress / cushion is used as a sensor. Also, there is a sensor set-up by Tsuchiya and colleagues who use S-shaped air tube. The following cases describe these recording set-ups in more detail.

Case1 , The measurement system by Watanabe and colleagues.

The measurement system designed by Watanabe and colleagues is based on the usage of air filled cushion with dimensions 450 mm x 90 mm x 5 mm what is directly connected to the sensor. In a earlier design (Watanabe and Watanabe, 2004) the changess of the air pressure inside the air cushion were detected with pressure sensor. The aquired signals were detected and processed with AGC and with envelope detector circuits.The signals were filtered in 3 bandwith areas: 0.1 – 0.5 Hz for respiration, 5 – 10 Hz for heartbeat and 100 – 500 Hz for snoring. In order to estimate HR and BR, FFT was applied with the sampling rate of 0.1 s and 512 data points. Based on the assumption that there are 6 sleep states(wake, REM, NREM 1, NREM 2, NREM 3 and NREM 4) and these states can be described with with single Markov process, a sleep estimation method was developed.

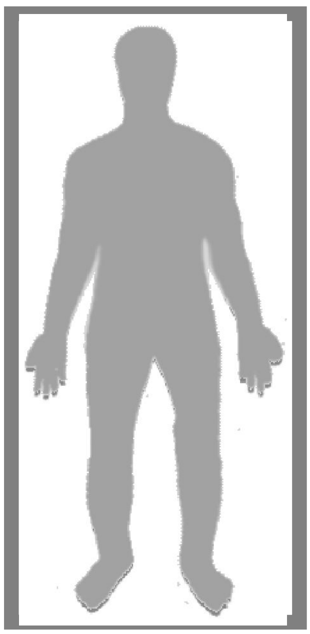

Figure 1. The sensor placement by Watanabe et al.

In a later design Watanabe (Kurihara and watanabe, 2012) used thermistor for detecting pressure changes inside the cushion. By the usage of analog bandpass filters, thermistor's output signal is separated into heartbeat and respiration components. However, before separating signal into components, a 50 Hz notch filter is applied. This pre-filtered signal is fed into 2 analog bandpass filters having cut-off frequences 0.9 Hz – 1.7 Hz and 0.1 Hz – 0.5 Hz.The heart activity component of the signal was exctracted with the usage of the combination of 6-th order low-pass filter with cut-off frequency 1.7 Hz and second order high-pass filter with the cut-off frequency 0.9 Hz.The respiration activity component of the signal was exctracted with the usage of the combination of 6-th order low-pass filter with cut-off frequency 0.1 Hz and 8-th order high-pass filter with the cut-off frequency 0.5 Hz. All the signals were sampled with 0.01 s interval. 100 data sets of 20 second long heart and lung activity signals were classified into 3 classes based on the strength of the signal-to-noise ratio: signals with SNR over 30 dB; signals withs SNR between 10 dB and 30 dB and signals with SNR less than 10 dB. In cases there SNR was more than 30 dB, a strong correlation between the pulse interval and HR and BR was found.

Case 2, The measurement system by Tsuchiya and colleagues.

This measurement system uses single air pressure sensor what is actually a tube, placed S-shaped inside a cushion (780 mm x 175 mm), 10 bit ADC and a full wave rectification circuit.The HR is detected as follows.A peak frequency of every 20 second signal is detected and a peak frequency of every 20 second signal is detected. Then the average frequency of 3 successive peak frequences is calculated. Based on the equation T = 1 / f; the point with maximum amplitude from 0 to T is determined as the initial heartbeat point. After this a fuzzy signal classificator with 2 rules is used. The first rule says that "large peak is caused by heartbeat" and the second rule says that "heartbeat interval does not change significally"(Tsuchiya et al., 2008).See Figure 2 about it.

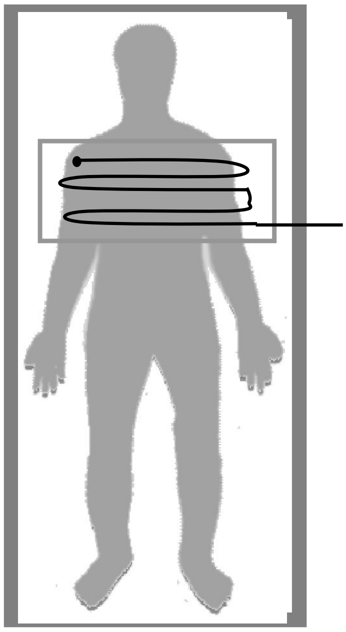

Figure 2. The sensor placement by Tsuchiya et al.

Multiple air compartment based systems

Case 1, A system designed by Chow and colleagues.

In order to detect ribcage and abdomen movements, Chow and colleagues(Chow et al., 2000) designed a air mattress sensing device there the mattress consists of mutiple separate air compartments and 4 separate air compartments under the thorax area are used for detecting ribcage and abdomen movements.The whole mattress size is 850 mm x 1900 mm x 40 mm when fully inflated. All compartments are inflated to 75 mbar air pressure. With the aid of four 3 meter long polyurethane tubes four air compartments under the thorax area are connected to two pairs of differential pressure transducers (Honeywell 163PCO1D75). If the differential pressure between compartments exceeds +/-5mbar, a solenoid valve is opened for 5 seconds and this equalises the pressure changes between air compartments. This helps to protect the transducers.

Case 2, A system designed by Chee and colleagues.

A system designed by Chee and Park (Chee and Park, 2005) uses a differential air pressure measurement method there two sensing tubes with balancing tube in between them is placed under the thorax area. The balancing tube is used because of 2 reasons: first, it helps to increase the sensitivity and secondly, it filters out common mode artefacts what are not related to heart and lung activity.The air mattress consists of 20 air filled cells and out of these 2 cells with balancing tube in between them are used for measuring heart and lung activity signals. The cells, filled with air at 10 kPa are 1 m long and have cylinder shape with the diameter of 110 mm. The balancing tube is 0.5 m long and has a rotational valve in the middle. The air pressure sensor is piezoresisitve sensor from Luca NovaSensor, NPC-1210. In this sensor piezoresistive strain gauge sensor is used in Wheatstone bridge circuit. The aquired signal was sampled at 200 Hz and digitized into 16 bits.The signal processing has been done with many different methods, for example by the usage of 8^{th} order Butterworth filter(Chee et al., 2005), Short Time Fourier Transform (Shin et al., 2006) and bandbass filters (Shin et a., 2010).

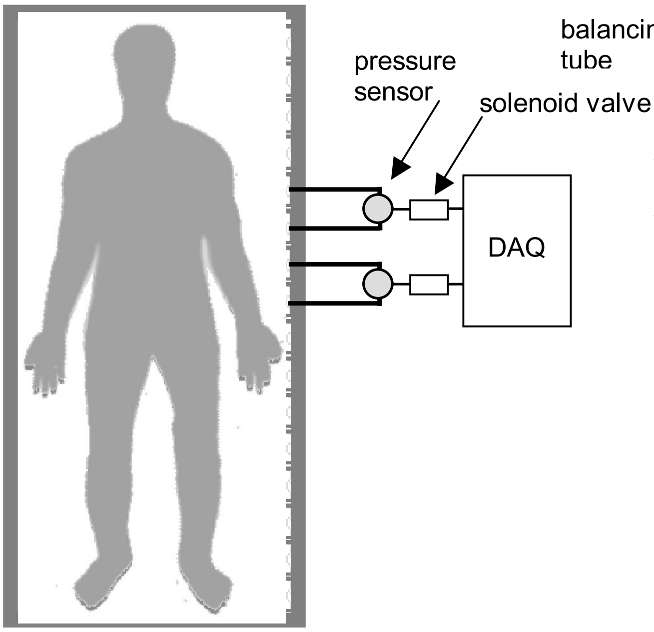

Figure 3. The sensor placement by Chow et al.

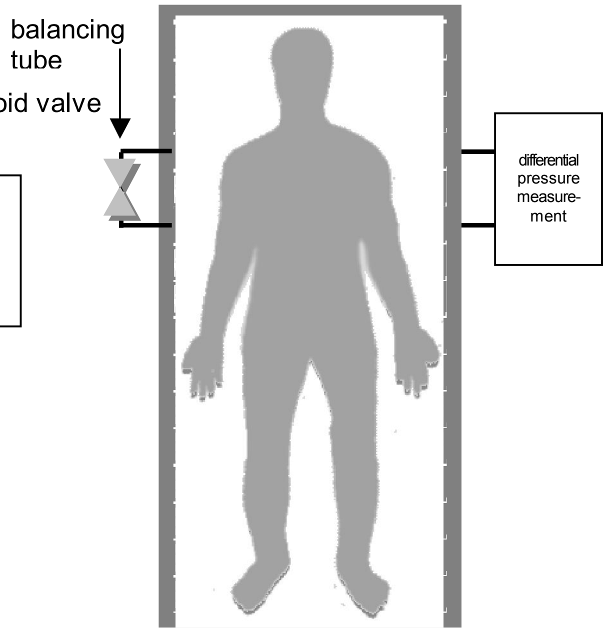

Figure 4. The sensor placement by Chee et al.

The special case: the useage of ultrasound and air pressure sensors

A system designed by Hata and colleagues in 2007 (Hata et al., 2007) consisted of a air pressure sensor and ultrasonic sensor and a fuzzy signal classification algorithym. The air pressure sensor consists of the air cushion with measurements 175 mm x 780 mm and pneumatic sensor, made of a piezo element and built-in charge amplifier , Fujisera, FKS-111.The signal is digitized with the 10 bit ADC. The ultrasonic sensor consists of a send and recive element with central frequency 2 MHz what is connected under a cylindrial water filled tank, 26 mm in diameter and 10 mm in height.The ultrasonic signal is transmitted to the water filled tank and the reciever detects the reflections from the water surface.By default, HR signal is aquired via the usage of the air cushion sensor but if there is no signal for 2 seconds, signal from the ultrasound sensor is used.

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2.6.7 Water filled tubes

measures

- heart rate
- breathing rate
- body movements

design principle

- pressure measurement

In the field of using water filled tubes for BCG signal detection two approaches can be seen: the pillow and the mattress approach.

Zhu and colleagues (Zhu et al., 2005; Zhu et al., 2006; Zhu et al., 2008) and Song and colleagues (Song et al., 2011) use pillows with water filled tubes as BCG sensors.

Heise and colleagues (Heise et al., 2010; Heise et al., 2011; Rosales et al., 2012; Su et al., 2012; Heise et al., 2013) place water filled tubes on the bed mattress, under the sheet. It should be noted that many different Hydraulic Bed Sensor sensor designs and layouts with theoretical backround information can be found from the Licet Rosales's MSc thesis: "Exploring Passive Heartbeat Detection Using a Hydraulic Bed Sensor System"(Rosales, 2011).

The pillow-approach. Using water filled tubes inside the pillow.

Case 1; The system designed by Zhu and colleagues.

In 2005 Zhu and colleagues (Zhu et al., 2005) designed a pillow what consisted of 2 incompressible polyvinyl tubes filled with air-free water placed parallel to each other between 2 acrylic plates.and 15 cm long arterial catheters what connected the sensor-pillow's sensor tubes to the KEYENCE Corp., AP-13 pressure sensors.The tubes, 30 cm long and 2 cm diameter had internal pressure 3 kPa and were separated 13 cm apart from each other. The recording setup can bee seen in Figure 1.

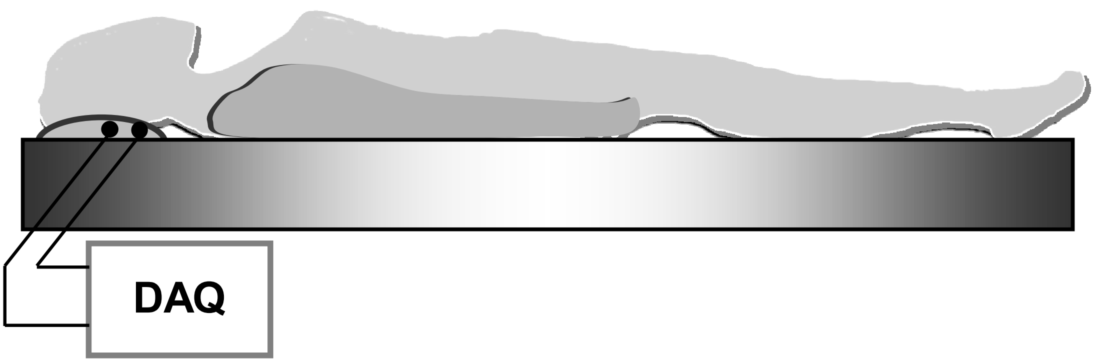

Figure 1. The sensor placement by Zhu et al.

During the measuremt process signals from two water filled sensor tubes and also finger photoplethysmogprahpy and nasal thermistor were recorded. All the signals were sampled at 100 Hz and digitized with a 16 bit ADC. The water filled tube sensor's signals were filtered in the band of 0.16 Hz and 5.0 Hz.

In 2006 Zhu and colleagues (Zhu et al., 2006) described the origins of the signals as following:"The static pressure component responds to the weight of a head, and the dynamic component reflects the weight fluctuation of a head due to breathing movements and pulsatile blood flow from the external carotid arteries around the head." Zhou and colleagues also found that breathing rythym signals can be easily detected from both sensor tubes but heart rythym signals can be adequately detected from the sensing tube closer to the neck. Two years later Zhu and colleagues (Zhu et al., 2008) advanced the system with the addition of TCP/IP netbox what transmitted the measured signals from the pillow to the server via TCP.

Case 2; A system designed by Song and colleagues.

In 2011 Song and colleagues (Song et al., 2011) designed a sensor pillow consisting of two waterfilled rigid plexiglass tubes placed between 2 plexiglass plates. The plexiglass tubes have measurements 300 mm in length and 5 mm in diameter and sealed from one end and connected to the pressure sensor ADP5131,Panasonic Electric Works, from the other end. The sensing tubes are placed parallel to each other on the 420 mm x 180 mm plate with 120 mm distance in between. In order to differentiate between heart and lung activity and snore induced signals, 3 different bandpass filters were applied: respiration signal was filtered in the bandwidth of 0.1 Hz – 1.0 Hz; heartbeat signal was filtered in the bandwidth of 0.8 Hz – 3.0 Hz and snore activity in the bandwidth of 90 Hz – 200 Hz. The heart and lung activity signals were sampled at 50 Hz and snore induced signal was sampled at 1000 Hz. After the evaluation the authors concluded that it was difficult to differentiate heart activity signal because of the strong respiration signal and environmental noise.

The mattress-approach. Using water filled tubes placed on the mattress.

Case 1; The system designed by Heise and colleagues.

In 2010 Heise and colleagues (Heise et al., 2010) designed a hydraulic sensor. The sensor body was made of 1.3 m long 3 inch wide (7.6 cm) discharge hose. One end of the hose was connected to a port that would allow of adding water and removing air. The other end was closed with a brass nipple (4.3 mm, inside diameter) to which approximately 1.5 meter long vinyl tubing was aconnected. This vinyl tubing connected the hydraulic sensor to piezoresistive monolithic silicon pressure sensor (Freescale MPX5010GS). The aquired sensor output signal is sampled by a 12 bit ADC at 10 kHz, low-pass filtered and downsampled to 100 Hz.In order to extract HR from the aquired pressure signal, the downsampled 100 Hz signal was filtered with a filter having cutoff frequency 20 Hz. After that windowed peak-to-peak deviation method was applied, searching for the most positive and the most negative signal values within a sliding window of 25 samples. This procedure is followed by 4 Hz low-pass filtering and segment extraction where a 10 second sliding window with 9 second overlap between the segments is applied. Finally, for determing the HR, autocorrelation is used for measuring the time distances between heartbeats.In order to extract respiration rate signal , a much easier algorithm was applied consisting of only 4 steps: low-pass filtering at 1 Hz, identifying 1 minute segments without motion artefacts, subtracting the DC bias from each segment and counting the zero-crossings and dividing the result by 2 giving the number of breaths per minute.

In 2011 Heise (Heise et al., 2011) advanced the previously developed Hydraulic Bed Sensor by adding hardware filtering circuit. Before digitizing with a 12 bit ADC at 100 Hz the aquired signal is amplified 10 times with 741 operational amplifier and after amplification 8th order Bessel filter Maxim MAX7401 with corner frequency 38 Hz is applied.

In 2012 Rosales and colleagues (Rosales et al., 2012) modified the design of the hydraulic bed sensor designed in 2011(Heise et al., 2011) because the previous version of the sensor did not provide distinguishable BCG segments and so the length of the tube was changed to 22 inches and the volume of the water was changed to 14 oz.The new modified sensor consists of 4 waterfilled sensor tubes, placed along the bed parallel to the body just like seen in Figure 2.

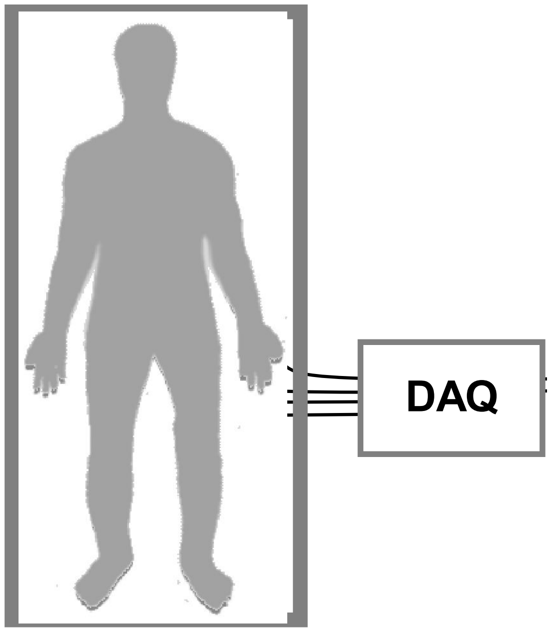

Figure 2. The sensor placement by Rosales et al., 2012

Each sensor tube is connected to the pressure sensor and the aquired signals are sampled at 100 Hz. After that sensor(s) who's output voltage exceeds the voltage threshold are selected. Signals from the selected sensor(s) are band-pass filtered at 0.4 Hz to 10 Hz and the feature, J-peak from the BCG signal is detected. Adter that k-means clustering method and beat-to-beat interval estimation is applied.

In the article published in 2013 Heise and colleagues (Heise et al., 2013) discussed the evolvement of the Hydraulic Bed Sensor in a more general context, trying to conclude the results achived in (Heise et al., 2010; Rosales et al., 2012; Heise et al., 2011; Su et al., 2012)with the emphasis on data collection via web portal and mobile devices.

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2.7 Temperature measurement based electronic beds

2.7.1 Introduction

Temperature measurement includes the usage of great variety of different methods. For example in a book edited by Webster 11 different temperature measurement methods are described(Webster, 1999). The whole topic of temperature measurement is too big to be covered in this sub-chapter. Therefore this sub-chapter describes only these sensors(thermistors and RTDs) what find usage in the design of electronically equipped beds. The interested reader should also read, subchapter 2.2.4, about body’s IR radiation measurement based beds. In order to get a complete picture about temperature measurements one should certainly read not only technical data sheets but also about the history and development of the field of science and therefore I recommend H. Chang’s book: “Inventing Temperature: Measurement and Scientific Progress”(Chang, 2004).

Measuring sleeping patient’s body temperature is a very complicated task because attaching sensors to the body would disturb the sleep but sensors embedded into the mattress are strongly affected by the surrounding envrironment’s temperature.There are very few articles describing the sleeping patient’s monitoring with temperature sensors embedded into the bed/mattress. Most of these originate from Tamura(Tamura et al., 1988; Tamura et al., 1992; Lu et al., 1999) and his colleagues work. These articles describe how to align thermistors in the bed in order to detect body movements and posture changes. Also this subchapter describes the usage of RTDs for temperature image map creation(Van der Loos et al., 2001; Van der Loos et al., 2003).

Problems to be encountered with.

Firstly, the surrounding environment affects the thermistors embedded into the mattress so much that it is not possible to detect accurate 2D temperature distribution. Secondly, thermistors are with slow response time and therefore it is difficult to detect movements. The number of sensors used doesn’t play any role at all because ambient temperature and blankets placed over the body disrupt the accurate temperature measurements.

2.7.2 Temperature measurement with thermistors

measures

- body movements

design principle

- resistance measurement

A thermistor is a resistor whose resistance changes with temperature. There are 2 different types of thermistors: those with negative temperature coefficent of resistance (NTC) and those with positive temperature coefficent of resistance (PTC). Typically thermistors have resistance in a range of few thousand ohms at room temperature. Usually thermistors are used for measuring temperature in the range of –50 °C to + 300 °C.Thermistors are available in many different sizes, shapes and values(Horowitz and Hill, 2001). A typical thermistor can be seen in Figure 1.

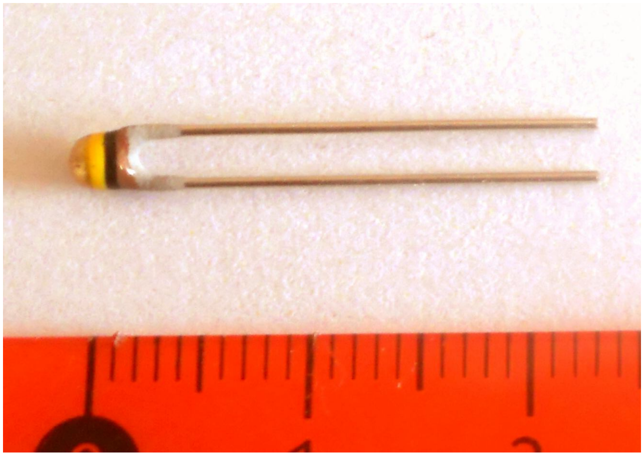


Figure 1. A photo of a typical NTC thermistor.

For signal conditioning many different circuits can be used but while measuring small changes of temperature a bridge circuit is recommended. Also the engineer has to take self-heating effects under the consideration.

In sleep medicine thermistors have been used for detecting body positions. The following describes the works done by Tamura and colleagues. These works describe 2 different thermistor placements in 3 pictures: the matrix layout(Figure 2 a) and the line layout(Figure 2 b and c).

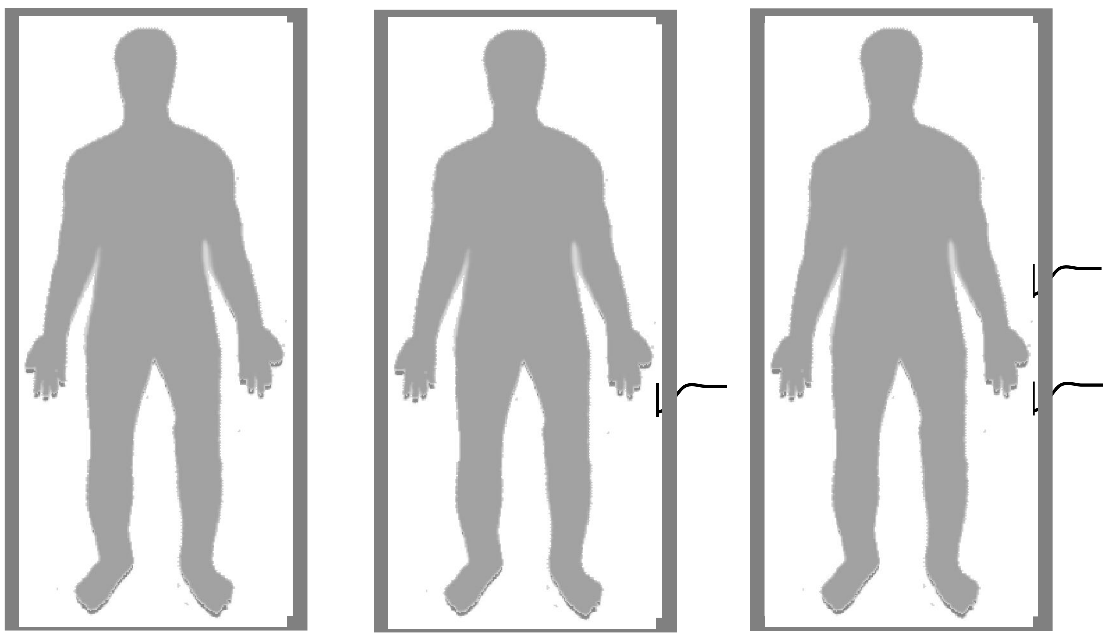
The matrix layout of the thermistors

In 1988 Tamura and colleagues (Tamura et al., 1988) designed a patient's body temperature measurement system where 15 sensors were aligned in a 3 x 5 matrix setup within 20 or 25 cm separation. One additional sensor was used for detecting the ambient temperature. In order to represent the resluts in a graphical form, the detected temperatures were classified into 5 levels: below 27°C, 27-30°C, 30-33°C, 33-36°C and above 36°C and displayed with different colors. This setup can be seen in Figure 2 a.

The line layout of the sensors

Based on the previous studies Tamura and colleagues found that elderly patients moved only little and temperature changes were slow. Through trial and error Tamura and colleagues found that straight line setup gives better spatial resolution than using the same number of sensors in the matrix setup and so in 1992 Tamura(Tamura et al., 1992) designed a temperature measurement system where 15 thermistors (PBN-41E, Shibaura Denshi, Tokyo, Japan) were aligned in a line, 6 cm apart from each other on the cable. One additional sensor was used for detecting the ambient temperature. The system recorded data after every 1, 5 or 10 minutes and stored it on the 16 kbyte RAM card. The accuracy of the thermistor was +/- 0.2 °C. After many tests, Tamura and colleagues found that this kind of recording setup is valid only for detecting postures. This setup can be seen in Figure 2 b. In 1999 Tamura and colleagues evaluated their straight line sensor setup based temperature measurement system with video recording and actigraphy.The result indicated that the system is capable to detect body movements.

In 1999 Lu, Tamura and Togawa (Lu et al, 1999) modified the 15 thermistor based straight line sensor system developed previously by placing two lines of thermisors—one under waist and one under lower limbs and created a new algorithm for detecting body movements. This time 15 thermistors were aligned in a straight line with 7.5 cm apart from each other. The sensors were placed under the bedsheet, perpenicular to the sleeping patient’s body and an additional thermistor was used for detecting the ambient temperature. After recording temperature and video camera data, it was found that the sampling interval 15 s is enough for accurately detecting body movement. Also, it was found that temperature measurements taken from the lower limb sensors was more accurate than the measurements taken from the waist area. This, improved system proved to be the most efficient out of these three recording systems and sensor setups (Lu et al.,1999). This recording setup can be seen in Figure 2 c.



Temperature measurement setups by Tamura and colleagues.

Figure 2a **Figure 2b** **Figure 2c**

2.7.3 Temperature measurement with RTDs

measures

- body movements

design principle

- resistance measurement

Resistance thermometers, RTDs, are used for measuring temperature in the ranges of –200 to + 500 C and have accuraccy in the range of +/- 0.25 to +/- 2.5 C(Webster, 1999). RTDs consist of ceramic substrate with platinum wire placed on it and covered with protective glass and interfaced with lead wires. This platinum wire acts as sensor element. RTDs are stable in time but the current what measures the sensor's resistance causes self heating (Joule heating). Usually self heating errors are small but sometimes can reach to 1 °C(Webster, 1999).

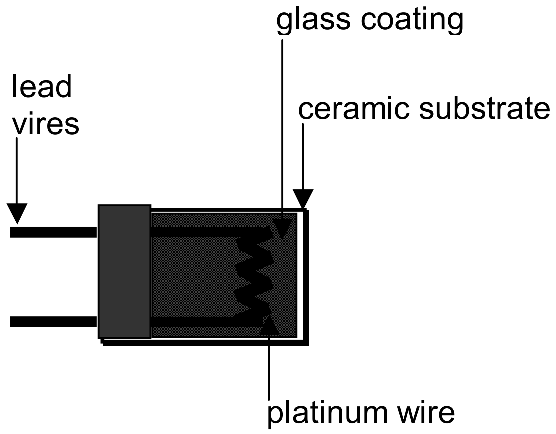


Figure 1. The structure of the RTD sensor.

On October 22, 2002 Van der Loos and colleagues received a patent, US 6,468,234 about a electronically equipped bed called SleepSmart. The bed was meant to measure sleep quality and lifestyle data(US 6,468,234). During the development process Van der Loos (Van der Loos et al., 2001; Van der Loos et al., 2003) used 54 RTDs as an additional supplement to the SleepSmart bed system. This temperatrure data is meant to control the mattress and/or room temperature. Although in the SleepSmart bed system RTDs do give information about body posture, the main focus is on measuring posture changes with 54 FSRs. This is a reasonable approach because the easiest ways to measure chest movements caused by heart and lung activity are pressure and capacitance measurement based methods. The importance of these two methods is that heart and lung activity generate vibrations and therefore BCG signal or any other pressure measurement based signal is highly correlated with cardioresoiratory activity.

Finally, it has to be said that measuring human body temperature in the bed with contact based sensors gives only information about body posture and some bigger movements. This information can be gained with other methos as well.

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Chapter 3

ELECTRONICALLY EQUIPPED BEDS USED IN SMART ENVIRONMENTS

3.1 Some smart environments used in sleep medicine

3.1.1 Introduction

Today one can say that there are 2 electronic data aquisition paradigmas: the research paradigma and the lifestyle paradigma. Although they have much in common, they are two different paradigmas.

The research paradigma is the paradigma we are used to think. It tells a story about the patient who goes to the hospital for the PSG study. When the doctor examines the 8 hour recording signals and makes the decision what to do next. Maybe some day some reasearchers also use this data but otherwise the case is closed.

In the lifestyle paradigma the patient lives in a environment what monitors the patient 24/7 and makes suggestions according to the patient’s aims. The environment consists of many different sensors, actuators and knowledge systems and much more. This has nothing to do with diagnosis or cure but it tracks the patient’s general health status and if needed gives warnings—for example an alarm or sends an e-mail to the doctor or SMS to the ambulance. This lifestyle monitoring paradigma also includes monitoring the patient’s health status during the night and if needed—make an advice to visit the doctor for conducting the PSG study.

This chapter gives a brief insight into 2 smart environment concepts: the ambient assisted living concept and the smart house concept. The ambient assisted living concept is ever so vague and hard to define but the smart house concept is well defined by now. These 2 subchapters describe the environments only because sensors attached to the body would disturb the sleep. The reader intersted in smart environments should complete the picture by adding Wireless Body Area Networks(WBAN) to the system.

3.1.2 Ambient Assisted Living

The term Ambient Assisted Living is very vague and hard to define. However, Constantine Stephanidis has given a very good definition in ERCIM News, Number 87, October 2011 and here it is:

> "AAL refers to intelligent systems of assistance for a better, healthier and safer life in the preferred living environment and covers concepts, products and services that interlink and improve new technologies and the social environment, with a focus on older people".

In 2014 Memon and colleagues wrote an overview article about AAL(Memon et al., 2014). This 30 page overview article describes 90 most relavant AAL articles published in between 2007 and 2013. They claim that they collected a total of 360 articles and also sent out 62 e-mail for conducting a survey. Unfortunately only 12 responded and out of this 12 only 8 provided information about their solutions. It is quite reasonable to think that the small amount of replies is related to keeping the business secrets. Because of this hard work done by Memon and colleagues this article gives a very good overview about the meaning of AAL. They describe in very detailed way how AAL usually consist of medical sensors, computers, wireless networks and software. They also mention the problem with data privacy.

In order to describe the AAL in more detail, 2 more articles are referenced. The article written by de Morais and Wickström (de Morais and Wickström, 2013) describes a "Smart Bedroom" and an article written by Ravichandran and colleagues (Ravichandran et al., 2015) describes a WiFi based breathing estimation environment.

Case 1. The Smart Bedroom

The "Smart Bedroom" (de Morais and Wickström, 2013) acts as a active database having sensors and actuators. The main component of the system is an ordinary bed with load cells under 4 legs. The bed uses Emfit's smart mattress. A Bluetooth based accelerometer is connected to the bed's upper frame for measuring the inclination of the back(shoulder section.The ceiling and table lamps are controlled with Telldus TellStick Duo. Motion sensors are used for detecting the presence of the person and also sound is recorded. The components of the system communicate with each other with the help of WiFi or Bluetooth. The software is written in C# and the database is done in PostgreSQL. These components are used for recording 3 different types of data: Medical Care, Independence and Comfort. The Medical Care data is HR, BR, movement in the bed, bed-exit alarm and center of the pressure. The Indipendence data is information about the lights, transfer support, weight assesment, time in bed, wake-up time, bed time and noise assessment. The Comfort data is automatic lightning, light control, bed adjustment and wakeup light.

Case 2. Detecting breathing rate with the usage of the WiFi.

The article written by Ravichandran and colleagues (Ravichandran et al., 2015) describes how to use 2.4 GHz WiFi for detecting breathing.In this example only single transmitter-receiver pair is used. The aim is to detect the breathing rate anywhere the house.The system uses Ettus Universal Software Radio Peripherial N210 as the backbone, having one such a device configured as a transmitter and the other as a receiver. The signal transmit power is configured to 15 dBm. Also, directional antennas LP0965 are used to enhance the signal's strength. The receiver demodulates the 2.4 GHz amplitude-modulated signal and samples it at 32 kHz. After this the signal is narrow-band filtered and demodulated. In order to minimize the signal's spectral energy it is futher down-sampled and filtered to the spectral range of 0.2 Hz to 1.0 Hz. The signal is also divided into 30s sliding windows, with 97% overlap between them. For signal processing Zero-crossing detection, FFT, Linear Predictive Coding and Least-Squares Harmonic analysis is used. They conclude that they can track breathing with the accuracy of 1.54 breaths per minute.

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3.1.3 The Smart Home concept

The Smart Home as a concept has become very popular because it is much more than using electro-automation inside the house and making sensor's data available in the internet. By today it has become a new field of science what enhances people's lives with various automation tricks but also includes various eHealth principles, devices and methods. Therefore the term "Smart Home" is hard to define. For example F. Kazmierzak(F. Kazmierzak, 2011) defines "Smart Home" as such:

> "A "smart home" can be defined as a residence equipped with a wide scope of computing and information technology which anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment in many ways through the management of technology within the home and connections to the world beyond."

However, there are various good review articles what describe the most important aspects of the "Smart Home". One such a good reveiw artictle is by Chan and colleagues (Chan et al., 2008). This review describes the fundamental principles of Smart Homes in general and also various Smart Home projects in the USA, Europe, Asia, Australia and New Zealand. The article concludes with the mentioning of wearable body area networks (BANs) what help to track the health status of the patient and exchange the data with the Smart Home and assistive robots.

The following 3 articles describe some of the most typical Smart Home types. These articles describe the usage of analog electronics, mixed electronics and various types of software usage.

Case 1. The uHouse

In 2004 (Seo and Park, 2004) wrote an article about a Smart Home what tracks resident's biosignals and life activities. The uHouse uses ADSL and Bluetooth for transmitting data from sensors into home PC and from home PC to central data server at Soul National University Hospital. The uHouse uses the following signals:

- The bed monitored ECG, respiration and body weight
- The toilet seat monitored ECG and body weight
- The room had a camera
- Flame sensor
- CO2 sensor
- Blood glucose, blood pressure and body fat
- Magnetic door switch

This helps to gather valuable medical data before the disease onset. Also, it has to be taken into account that these sensors may interrupt patient's privacy. Therefore the design of the Smart House has to take into account possible side-effects. The designer has to consider what kind of sensor data is really valuable and what kind of data pushes the limits of patient's privacy.

Case 2. The 3 layer system: from wearable body network to the intelligent medical server

An article written by Shahriyar and colleagues (Shahriyar et al., 2009) describes 3 layer Intelligent Mobile Health Monitoring System what consits of Wearable Body Sensor Network (WBSN), Patient's Personal Home Server (PPHS) and Intelligent Medical Server (IMS). The WBSN collects patient's personal medical data from various sensors to the PC, cell phone or PDA. The WBSN uses a microphone, ECG, temperature and SpO2 sensor, an accelerometer and a non-invasive blood pressure measurement device.The WBSN's central controller uses Bluetooth, WLAN or ZigBee. The PPHS collects data from the WBSN and sends it to IMS. This article is another example about the usage of various data layers, software and servers.

Case 3. The Smart Health Home

An article written by Choukeir and colleagues (Choukeir et al., 2010) about the Smart Health Home describes the mixed usage of analog and digital electronics and software engineering for recording the ECG, HR, patient's body core temperature, falls and finally the system reminds the usage of medications. The data gathered is transmitted with ZigBee.

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3.2 Smart mattresses: the hospital approach

3.2.1 Introduction

So far the book has concentrated on the data aquistion principles of the smart beds/mattresses and expecting that the bed/mattress has one or few users. The usage of networking helps to integrate many beds into one big system and can be useful when there are many bed users, for example in the hospitals. In that case the bed becomes one item of the hospital information system and serves partially as a diagnostic device but also partially as the electronic medical record. For example the bed can detect all the nurses and doctors who have been around (assuming they wear RFID).

Smart networked beds can supply the nurses with information about the patient's presence of the bed, fall out or sudden changes in heart or breathing rate. This means that the bed collects long-term data about the patient's health status and gives emergency alerts. The bed's ability to call for help could be seen as an advancement of the nurse-call technology because during the emergency the patient himself might not be able to press the nurse call button.

3.2.2 Some examples about the existing devices and technologies

Electronically equipped beds have been around for some time, however the focus has been on adjusting the bed positions. Beds monitoring heart and breathing rate are quite new and not well spread in the hospitals. Some of the electronically equipped beds designed for ICU measure heart and breathing rate but this is another topic. The following 4 cases give a brief overview about this ever-growing area.

Case 1. The multi-sensor based smart bed by Bustamate and colleagues.

In 2008 Bustamante and colleagues (Bustamante et al., 2008) described the design of intelligent bed what tracks the presence of the patient with shock and acceleration sensor and with extensiometric gauge placed on the bedrails. Also this intelligent bed measured patient's position with pressure sensors placed on the mattress area, height scaled placed under the bed legs and finally it also included IR sensor and video camera.

Case 2. The Emfit SafeBed

The promotional material about Emfit SafeBed says that it is a networked (IP) nurse-call system with passive patient monitoring. The working principle of the Emfit bed sensor is described in subchapter 2.6.4. The sensor detects heart and breathing rate and body movements. The bed also includes alarm function. The bed itself is interfaced into local area networks (LAN or WLAN)(www.emfit.com).

Case 3. The pressure sensitive bed sheet designed by Huang and colleagues

In 2013 Huang and colleagues (Huang et al., 2013) designed a e-textile pressure sensitive bed sheet for HR measurement. The bed sheet has dimensions 2.5m x 1.25m and contains 64 x 128 pressure sensors, 64 columns and 128 rows of conductive lines. These 8192 pressure sensors are quantified 8 bit, having values from 0 to 255 where 255 represents (lowest e-txtile)maximum detectable pressure. The sampling rate can be as high as 10 Hz but is set to 1.5 Hz. An Android is used for gathering the sensor data and the software uses 5 different states: No User, Initialization, Respiration, Apnea and Motion. The data is written into time-stamped comma-separated value (CSV) file.

Case 4. The capacitive lead system by Eilebrecht and colleagues

This is a capacitive system what uses 8 sensing electrodes and 1 ground electrode and is described in subchapter 2.4, Case 4, Figure 6. The electrodes are placed in a 3x3 matrix layout under the chest area.

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Chapter 4

REMOTE AND UBIQUITOUS SLEEP MONITORING SYSTEMS

4.1 Radar

4.1.1 Introduction

The radar is a data aquisition device with long history and many applications. The founding principle and the first radar-like was first developed by Christian Hülsmeyer in 1904 and later several times re-descovered. However he was too much ached of his time and people were not interested in his “telemobiloskop” device. In 1922 Marconi picked up the radar principle but with no great success. In 1925 Breit and Tuve used pulses in the range of 3 to 30 MHz to measure the heights of ionosphere. However, before the start of the II World War(1939), France, Soviet Union, Japan, Italy and The Netherlands had radar systems(Holpp). In 1942 de Rosa filed a patent for impulse radar but actaully UWB radar age started in the 1990s(Aardal and Hammerstad, 2010). The exact history of the radar is long and related to the history of the II World War(Holpp). More details about WW II time radar history can be found(Swords, 1986).Today there are many different types of radars and huge amounts of books describing them. In order to set the scene, let’s have a look on radar classifications.

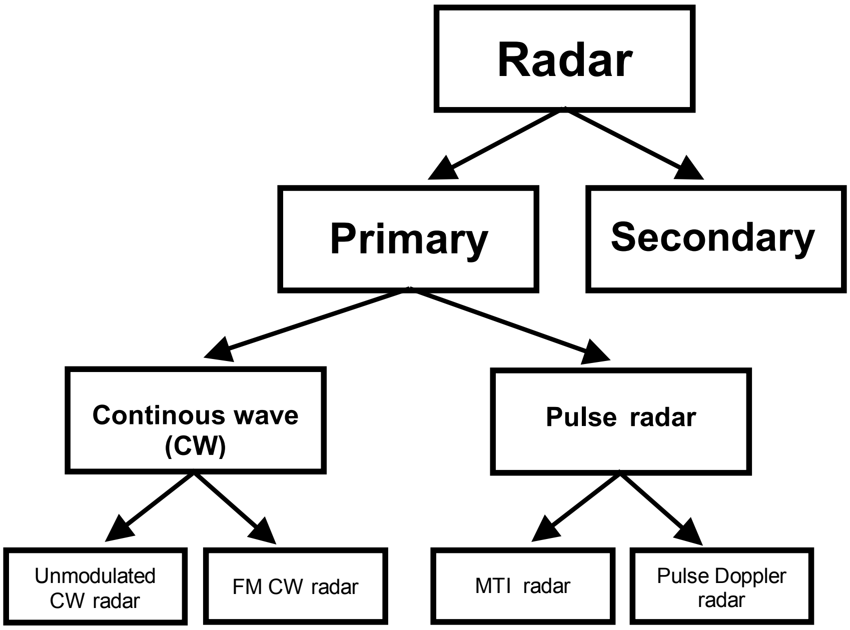

Figure 1. The classification of radars

Primary radars transmit the signals and wait for the reply. Secondary radars are radars what send out signals what activates the transponder system and when detect the transponder system’s reply. This is a system used in the airplanes. Talking about the primary radars, there are radars what transmitt continous wave high frequency signal and radars what transmit only pulse signals.

The radars were introduced to medicine in the 1970s(Aardal and Hammerstad, 2010). Aardal and Hammerstad claim that the first radar respiration(by Carlo and Bloice) and heartbeat(by Kazamias et al) measurements were done in 1971(Aardal and Hammerstad, 2010). The overiew article stands out for it's clarity and should be advised. Considering the fact that there are many different classes of radars and the radars are very complex devices, the following sub-chapter describes only two types of radars what find usage in the sleep medicine: the Doppler radar and the UWB radar.

4.1.2 The usage of UWB radars in sleep medicine

The UWB radar is a new but well spread radar technology in sleep medicine. There are many overview articles describing the UWB radars development history(Barrett, 2000) and usage in medicine(Varotto and Staderini, 2011; Paulson et al., 2005). Although most of the articles what describe the usage of radars describe the radars placed outside the bed, radar based bed mattresses do exist(Taylor, 2013).

Case 1. The UWB radar by Nijsure and colleagues

In 2013 Nijsure and colleagues(Nijsure et al., 2013) designed a system for respiratory monitoring. The system uses Impulse Radio Ultrawideband (UWB) signals generated and received with 2 pairs of antennas.The UWB pulses are generated with Picosecond Pulse Labs' 3500D impulse generator what produces pulses with pulsewidth 80 ps. The bandwidth of the signal is approximaztely 4 GHz. Agilent DSO81204B real-time wideband digital oscilloscope with sampling rate 40 GHz is used for recording signal scattered from the chest.

Case 2. The UWB radar by Lai and colleagues

In 2011 Lai and colleagues (Lai et al., 2011) designed a system for sleep apnea monitoring.The system is based on the principle that a train of subnanosecond pulses is created and transmitted to the patient and a vector network analyser is used for measuring frequency response of the backsattered signal.This method measures pulse disposition in the time domain and this is useful because pulse disposition in the time domain is linearly related to the chest movement.The UWB pulses were created with Picosecond Pulse Labs' 3500D impulse generator what generates Gaussian pulses with a full width at half maximum of 80 ps. Agilent DSO81204B real-time wideband digital oscilloscope with a sampling rate of 40 GHz is used for recording backscattered signals from the chest. The transmit and receive antennas are placed parallel to each other with 5 cm distance in between.The oscilloscope records the backscatered radar pulses with the rate of 5 Hz. Fourier transform is used for getting the frequency power spectrum of the respiratory rate. The signals are aquired with the program written in Labview and signal processing is done in Matlab.The system was tested by 4 subjects in normal conditions and 1 subject during sleep. The patient slept 4 hours on the mattress placed on the floor and the antennas were placed 0.8 m on top of the subject.In order to improve the accuracy of the detected signal, a multipeak detection method is used. Within this method many peaks-subpeaks are detected and the results are averaged. The tests showed that increasing the number of peaks-subpeaks increased the accuracy of the results. Maximum 3 peaks-subpeaks were used.

Case 3. The UWB radar Zito and colleagues

In 2011 Zito and colleagues (Zito et al., 2011) designed a SoC UWB pulse radar sensor for monitoring respiration. The system is realized in 90 nm CMOS technology. The pulse generator generates short pulses and sends these pulses out and these pulses reflect back from the subject under test. The reflected signals are first captured by the antenna and when amplified and correlated (multiplied and integrated) with the delayed replica of the transmitted pulses. Averaging a large number of pulses helps to increase the signal-to-noise ratio.The delay generator produces a delay equal to the time-of-flight of the transmitted and received pulses. When the target is not moving, the local replica and the amplified echo are aligned and the multiplier provides the same output pulse . The signal at the output is constant .When the target is moving, the moving causes a time-varing between the local replica and the echo amplified by the LNA.The radar sensor is thought to operate either in ranging mode (RM) or tracking mode (TM). In RM the delay generator provides a variable delay in order to span the range of interest and identify the target. When the object is targeted, the radar switches to the TM where the delay generator produces fixed delay. In order to have better immunity to noise and EMI the circuits are built in fully differential topologies.

4.1.3 The usage of Doppler radars in sleep medicine

There Doppler radars have been in use for lot of time.The first Doppler radar based respiratory rate measurements were done in 1975 and in 1979 first Doppler radar based heart rate measurements were done(Boric-Lubecke, 2009). A lot of valuable information about the usage of the Doppler radars in sleep medicine can be found(Zakrzewski, 2015).

Case 1. The SleepMinder Doppler radar sensor by BiancaMed

In 2011 Chazal and colleagues (Chazal et al., 2011) designed radar system what is able to measure sleep and wake states of the patient and visualize respiratory movement signals.The device used is called SleepMinder, designed by BiancaMed in Dublin, Ireland.

The sensor emits two pulses of radiofrequency energy at 5.8 GHz (each pulse is approximately 5 ns long). The first pulse acts as the main transmit pulse and the second pulse is the mixer pulse.The first pulse reflects off nearby objects to create an echo pulse that is received back in the sensor. Moving objects such as a pearson breathing generate a variable phase shift that can be detected by the electronics. The sensor is designed to be directional (only measures movement in front of the sensor) and range-limited(it only responds to objectcs which are within 2.5m of the sensor). The noncontact biomotion data signal was aquired silmutaneuously with EEG, EOG, ECG and ribcage respiratory effort using the Biopac MP100 data aquisition system. After acquisition, the data were converted to the EDF format for further processing. The system uses quadrature detection, outputing two analog voltage signals, I and Q signals.

Case 2. The Doppler radar based sensor by Rahman and colleagues

In 2015 Rahman and colleagues (Rahman et al., 2015) designed a short range radar system for measuring body motion, heart rate and breathing rate. The system consists of the embedded system unit and smartphone unit.The radar works at 24 GHz, consuming 28.5 mA at 5V and the total power consumtion of the system is 0.546 W. The system works within the distance up to 2 meters. The signals are filtered with Butterworth filters.The system uses Sleep vs Wake classifier, REM vs NREM sleep classifier and Sleep Quality Measurement: Sleep Onset Latency, Number of Awakenings, Total Sleep Time, Sleep Efficiency. These parameters are calculated based on complicated statistic methods.

Case 3. The Doppler radar based AHI detector by Suzuki and colleagues

In 2013 Suzuki and colleagues (Suzuki et al., 2013) designed a system what was based on two 24 GHz microwave antennas placed below the mattress. The radars were placed 70 cm above the top of the mattress. The radars have average output power 7 mW and maximum output power 10 mW. In order to avoid channel overspeak antennas work on different frequences: one antenna at 24.110 GHz and the second antenna at 24.150 GHz.The microwave radar's signals were sampled at 100 Hz. The signals were band-pass filtered: the cardiac filter had 0.5 Hz and 2.5 Hz and the respiratory filter had 0.05 Hz and 0.5 Hz. After band-pass filtering FFT with Hanning window was applied.The software was written in Labview.

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4.2 Ultrasound

4.2.1 Introduction

The ultrasound is sound having frequencies 20 kHz or more and it can be created and/or detected with piezo crystals. Sometimes one piezo element is used for both, signal generation and detection.The ultrasound sensor is based on the idea that ultrasound signal is sent out and the reflections from the object are detected. The reflected signal's quality depends on the densities of the environments the signal has to pass through. The image detail depends on the frequency of the ultrasound. The higher the frequency, the finer the image. A typical ultrasound sensor is shown in Figure 1.

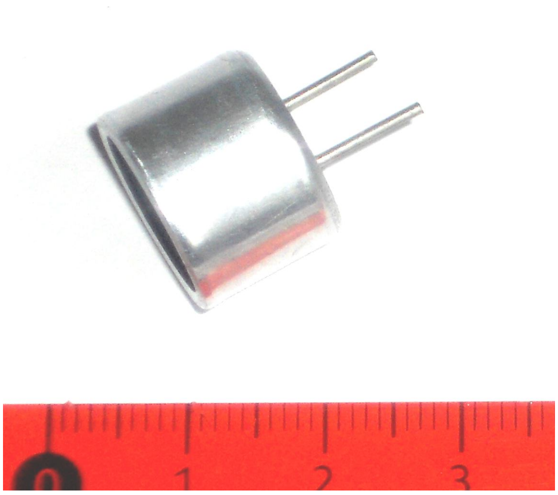

Figure 1. A typical ultrasound sensor.

The most important part of the history of ultrasound is the year 1880 when Curie's discovered the piezoelectric effect but it took quite a lot of time before ultrasound started it's progress. The reason was technological because by that time electronics was in it's early development stage and before L. D. Forest invented the vacum tube, in 1907, there was no way to amplify electronic signals(Erikson, Fry and Jones, 1974).Possibly the earliest work using ultrasound in biology and medicine is by Wood, R. and Loomis, A., "Physical and Biological Effects of High-frequency Sound Waves of Great Intensity," Phys. Rev. (2),29, S. 373 (1927). In 1942 Karl Theodore Dussik, a neurologist at the University of Vienna measured the transmission of ultrasound beams through the head(Bálint, 2002).The first real time medical ultrasound images were aquired between 1953 and 1955 by Dr Douglas Howry, Dr Joseph Holmes, Dr John Wild and professor John Reid. In 1957 first commercial ultrasound machine, the "Diasonograph" was created.In 1959 professor Ian Donald detected ultrasound echoes from the fetal head(Wingfield, 2012).Today there are many articles describing the usage of ultrasound in medicine(Carovac,Smajlovic and Junuzovic, 2011).

4.2.2 Some examples about the existing devices and technologies

In sleep medicine there is always a problem how to monitor the patient without interrupting the sleep. Because of this researchers try to invent new contact-free patient monitoring devices. Ultrasound has been used in medicine for quite a long time and therefore it seems very appealing to use it for monitoring the sleeping patient. However, one of the problems with ultrasound is that the patient moves during sleep and this makes the signal detection difficult. The following 3 cases describe the usage of ultrasound sensors for monitoring the sleeping patient's breathing and heart rate.

Case 1. The usage of air pressure and ultrasound sensors by Hata and colleagues

In 2007 Hata and colleagues (Hata et. Al., 2007) describe a bed what uses air pressure sensor and ultrasonic sensor system. The air cushion has size 175 mm x 780 mm. The ultrasensitive pneumatic sensor is Fujisera, FKS-111. The ultrasound sensor is placed inside cylindrical tank which has diameter 26 mm and 10 mm height and filled with water. The sensor is placed on the bottom of the tank and works at 2 MHz. The ultrasonic wave reflects on the water surface and the reflected waves are aquired at 20 msec and are quantizied to 10 bits.The heart rate is detected with the help of Fuzzy rules. The system is built so that usually it outputs air pressure sensor's output but when the air pressure sensor has not produced any signal for 2 seconds or the data is wrong, when the ultrasonic sensor's output is used.

Case 2. The ultrasound based pulse rate monitor by Tsukamoto and colleagues

There are at least 2 versions of the ultrasound based pulse rate sensor. The differences are in the number of recieve sensors used. See Figure 2 a and b about it.

In 2011 Yamana and colleagues (Yamana, Tsukamoto and Mukai et al., 2011) designed a system for non-contact pulse rate, respiration rhythm and body movement monitoring.The system is based on the usage of Nippon Ceramic's 40 kHz ultrasound transmitter and receiver pair T40-16/R40-16. The ultrasound sensor pair is placed 770 mm from the foot side. The ultrasound transmitter circuit consists of 40 kHz sinusoidal oscillator,gain controller and ultrasound transmitter.The ultrasound receiver circuit consists of the ultrasound receiver sensor, 40 dB amplifier, envelope detector, 4 band filter, ADC(12 bit 8-channel ADC, National Instruments, USB-6009) and a PC. After passing the envelope detector the signal is fed into 4 band filter. The respiration filter has limits 0.2 Hz – 0.7 Hz, the heartbeat vibration filter has limits 5 Hz – 20 Hz, the body movement filter has limits 1 Hz – 20 Hz and the bed in/out detection is based on the usage of 0.1 Hz. See Figure 2 a about the placement of the sensor.

In 2013 Tsukamoto and colleagues (Tsukamoto et al., 2013) modified the previous system by adding another ultrazsound receive sensor. The system uses one ultrasound transmitter and two ultrasound receivers connected to the wooden plate.The sensor layout is seen in Figure 2 b. The detected signal is conditioned with a 13-30 Hz band-pass filter and a 40 dB amplifier.

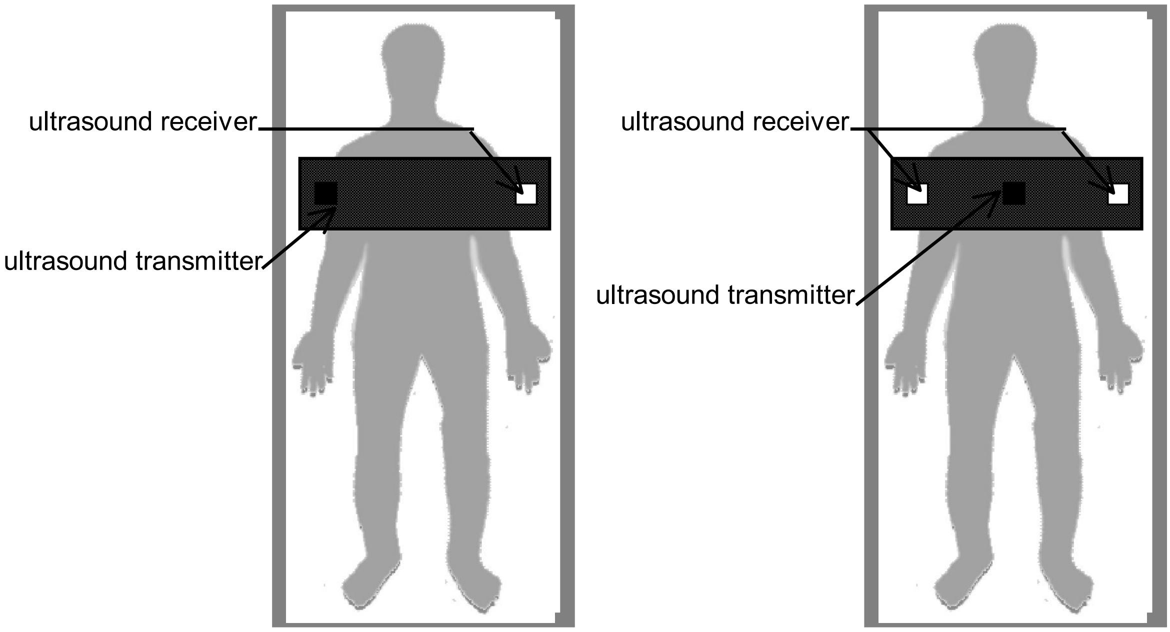

Figure 2 a. **Figure 2 b.**
The placement of the ultrasound sensors by Tsukamoto and colleagues.

Case 3. The ultrasound based breathing monitor by Arlotto and colleagues

In 2014 Arlotto and colleagues (Arlotto et al., 2014) designed a ultrasound sensor based breathing monitor.The system is based on generating 40 kHz ultrasound. The transmitter is placed close to the patient's head, at a distance of 50 cm and the receiver is placed at a distance of 30 cm from the head.The system uses a frequency mixer and it mixes the 40 kHz ultrasound transducer signal with 44 kHz sinusoidal signal.The signal is processed with 16 bit / 44100 Hz PC soundcard.

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Chapter 5

BED EXIT DETECTION SYSTEMS

5.1 Person based bed exit detection systems

The person-based systems are systems where the sensor is connected to the patient. Quite often this is found to be disturbing and therefore these systems are not very popular. An article written by Chou and colleagues (W-C.Chou et al., 2013) describes a fall detection system based on the usage of the accelerometer attached to the patient's chest. Another, more complicated person-based system based on the usage of accelerometer attached to the chest is designed by R.L.S. Torres and colleagues and it uses wireless wearable RFID tag, a WISP what consists of the 3-axial accelerometer ADXL-330 and a microprocessor (MSP430F2132) what is powered by the electromagnetic energy(R.L.S. Torres et al.,2013).This is a very simple and effective method.

5.2 Bed based bed exit detection systems

Systems what use sensor(s) connected to the bed are always able to detect such a simple thing as the presence of the patient and therefore bed-based systems are the most wide spread ones. Most of this book has described various complex bed-based systems what were used for monitoring HR and BR. Therefore bed-based systems are described only very briefly here. For example Bruyneel, Libert and Ninane describe the usage of the bed-exit system what uses 3 signals: the presence, body motion and temperature(M.Bruyneel, W.Libert and V.Ninane, 2011). Pouliot and colleagues describe the usage of Bed Occupancy Sensor, a waterproof 80 cm x 30 cm mattress what consits of 24 pressure sensors what communicate with PC with the Bluetooth connection(Pouliot et al., 2012).

5.3 Room based bed exit detection systems

There are many different ways how to design room-based systems and the results are very distracted. For example IR, radar and ultrasonic sensors can be very easily installed but the usage of camera always causes trouble with privacy. Because of this some simple tricks are used, for example the usage of sensitive floor mats. One such an example is a intelligent floor sensing using an array of resistive pressure sensors(Morgado and König, 2012).An article written by Wai and colleagues(Wai et al., 2010) is a good example of the combination 2 types of systems, the bed-based systems and room-based systems. The system uses a mattress made of 56 FSRs (Force Sensing Resistors) (bed-based system) and a video camera, Passive Infrared Sensor(PIR) and ultrasonic sensor(room-based system).The interested reader can find a lot of articles what describe multi-modality sensor systems but the reader has to consider two simple things: "what is needed?" and "less is more". First of all, what is the problem to be solved ? And secondly, although sometimes data redundancy may be important, too many data can also cause trouble.Articles written by Madokoro and colleagues (H.Madokoro, N.Shimoi and K.Sato,2013a;H.Madokoro, N.Shimoi and K.Sato,2013b) give overviews about different types of sensors(considering the bed exit problem) and the timing, cost, accuracy and privacy aspects related to each type of sensor.

Finally, nurse call systems have to be mentioned. Nurse call systems may use many different types of sensors and therefore we are not going to re-discuss the design of it. Here nurse call systems are mentioned because we want to emphasise the importance of help. The smart beds using various different sensors for patient monitoring emphasised the HR and BR but only seldom used help call feature. Compared to HR and BR measurement and OSA detection, adding the help call feature is very simple but it can help to save lives, specially in the hospitals. A good help call feature should consist of at least 2 parts: the automatic part what monitors the patient's stay in the bed and a classical help button. Considering the fact that in some cases the patient may not be able to move himself/herself a good help button can be realised as a watch having an accelerometer built in for detecting the falls. This "watch" should also have one big visually identifiable button for calling the help. Therefore a good system is a well combined system, having taken the best from each field, for example the bed may include a sensor for HR and BR detection, the patient have a watch for calling the help and the room has video camera for making sure everything is all right.

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APPENDIX 1. BABY MONITORS

Appendix 1. Baby monitors

Introduction

The babies have different sleep structure than adults have. Saying with few simple words, they sleep almost all the time. The parents have to take care of their little ones and this rises the question about the necessities. Today people are used to the paradigm that everything has to be electronical but only rarely think if it is necessary. You have to think about your necessities first and make plans so that they are realistic. Do you have one or many children ? Do you use only 1-room flat or a large house ? Do you want to check your child's breathing only or do you want to have some talk-back with your child when he/she grows older? Answers to these simple questions help you to make certain, do you want to buy a baby monitor and if, when what type of one.

This appendix classifies baby monitors according to 3 principles: person-based, room-based and bed-based baby monitors. The person-based baby monitors are baby monitors what are somehow connected to the baby's body, like electrodes made of smart textile. The room-based baby monitors are baby monitors what measure the environment surrounding the baby. The bed-based baby monitors are monitors where the bed/mattress is acting as the sensing device.

Person-based baby monitors

Person-based baby monitors are baby monitors where the sensor element is in contact with the person under the investigation. These monitors can also be classified as wearable electronic devices. Compared to other baby monitors person-based baby monitors always detect the strongest signal.

Case 1. The usage of the strain gauge sensor

In 2007 Ciaccio and colleagues (E.J.Ciaccio et al., 2007) wrote an article where they described the monitoring of infant's breath with the strain gauge sensor. The transducer is made of 28 cm long foam rubber belt with velcro tabs connected to the ends and electrodes embedded in the central area of the rubber belt. The belt's tension was monitored with 2 piezoresistive elements from Kulite Semiconductor Products. The transducer uses two 9 volt batteries for providing two-sided supply(for 55 hours). It is noteworthy that this article also includes signal conditioning circuit.

Case 2. The usage of photoplethysmography

In 2012 Daly, Monasterio and Clifford (Daly, Monasterio and Clifford, 2012) wrote an article where they described how PPG sensor and Android(smartphone) have been used for neonatal apnea monitoring. 4 different types of variables were recorded: SpO2, HR, Br and spectral purity. Also audio and actigraph signals were recorded and stored as text files on the phone. Additional information about the usage of PPG sensor based baby monitor can be found in a work done by Leier(Leier, 2013).

Case 3. The usage of smart textile

In 2011 Chen and colleagues (Chen et al., 2011) designed Smart Jacket with textile sensors for 1-lead wireless ECG monitoring. The sampling frequency is 198 Hz, and the system is based on IMEC’s UniNode module what uses Texas Instruments’s MSP430 microcontroller, Nordic nRF24L01 2.4 GHz radio and is powered with 165 mAh lithium-ion battery. The wireless transmission uses TDMA network protocol and the data is processed with MATLAB.

Bed-based baby monitors

Typically bed-based baby monitors are smart mattresses what measure heart and breathing rate.Within this book the entire chapter 2 describes data aquistion methods used in bed-based systems. While talking about baby monitors the size of the electrodes can be smaller but otherwise the electronic circuitry and system design remains the same.

Room-based baby monitors

Room-based baby monitors are baby monitors what use sensors what measure either the environment or make usage of the non-contact remote sensing technologies like video, radar and ultrasound(See chapter 4 about it). Room-based monitors can be integrated into the house network but this is a serious security threat(Read Case 2 about it!).

Case 1. The usage of IR thermography

In 2011 Abbas and colleagues (Abbas et al., 2011) wrote an article there they described IR thermography for monitoring the neonatal’s respiration. The IR camera was placed 70-80 cm from the neonate, aimed at the nostril’s area. They also composed complex thermal signature’s model and described a lot of specific physics and physiology in their long-run research article.The temperature difference between the in-haled and ex-haled air was between 0.3 C and 0.7 C and the data collected was processed with Matlab. However the results gathered were not very specific and they also presented the idea that it is much easier to monitor adults with IR thermography whan neonates.

Case 2. The usage of the video: the security threat

There are very many different video based baby monitors available and some of them transmit video data through internet. This could be a serious problem when someone hacks into the house network and takes control over the video and voice recordings.Some video based baby monitors transmit their video data in such a primitive way that neighbours can have live broadcast about everything happeining in your place. More details about the privacy issues of the usage of the video monitors can be found (https://nakedsecurity.sophos.com/2013/08/14/baby-monitor-hacker-spies-on-and-swears-at-sleeping-2-year-old/).

Case 3. The multi-sensor approach

In 2014 Rajesh and colleagues (G. Rajesh et al., 2014) designed a multi-sensor baby monitoring system with wireless sensor networks (WSN) what uses video, detects crib fencing, monitors crib’s temperature, room light intensity, baby’s wheight and reminds when to vaccine. The system is built on the usage of MIB520CB (Base Station for WirelessSensor Networks), Smart Phone and IP camera.

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