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Monitoring sleep quality with non-invasive sensors

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ABSTRACT OF LICENTIATE THESIS

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Abstract

Sleep is an important part of health and well-being. While sleep quantity is directly measurable, sleep quality has traditionally been assessed with subjective methods such as questionnaires. The study of sleep disorders has for a long time been confined to clinical environments, and patients have had to endure cumbersome procedures involving multiple electrodes placed on the body. Recent developments in sensor technology as well as data analysis methods have enabled continuous, unobtrusive sleep data recording in the home environment. This has opened new possibilities for studying various sleep parameters and their effect on the quality of sleep.

This thesis consists of two parts. The first part is a literature review examining the field of sleep quality research with focus on the application of intelligent methods and signal processing. The second part is a descriptive data analysis look at sleep data obtained with non-invasive sensors.

Keywords: sleep analysis, sleep quality, non-invasive sensors, ballistocardiography

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Tiivistelmä

Uni on terveyden ja hyvinvoinnin keskeinen tekijä. Unen määrä on helposti mitattavissa, mutta unen laatua on perinteisesti seurattu kyselylomakkeiden kaltaisin subjektiivisin menetelmin. Unihäiriöiden tutkiminen on pitkään rajoittunut kliinisiin ympäristöihin, ja potilaiden on täytynyt sietää hankalia tutkimusmenetelmiä useine kehoon kiinnitettävine elektrodeineen. Anturiteknologian ja data-analyysimenetelmien kehittyminen on mahdollistanut unidatan jatkuvan ja huomaamattoman tallentamisen kotiympäristössä. Tämä on avannut uusia mahdollisuuksia sekä unen ominaisuuksien että niiden unen laatuun vaikuttavien tekijöiden tutkimiselle.

Tämä tutkimus jakautuu kahteen osaan. Ensimmäinen osa on kirjallisuuskatsaus unen laadun tutkimukseen, painopisteenä älykkäiden menetelmien ja signaalinkäsittelyn soveltaminen. Toisessa osassa esitellään huomaamattomilla sensoreilla kerättävän unidatan tutkimista ja sen deskriptiivistä data-analyysiä, esimerkkinä ballistokardiografia.

Avainsanat: unitutkimus, unen laatu, huomaamattomat sensorit, ballistokardiografia

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Nomenclature

BCG	Ballistocardiography; measurement of ballistic forces on the body induced by the pumping action of the heart.
CSR	Cheyne-Stokes respiration
ECG	Electrocardiography; measurement of the electrical activity of the heart using electrodes attached to the skin.
EEG	Electroencephalography; the recording of electrical activity, resulting from ionic current flows within the neurons of the brain, along the scalp.
EMG	Electromyography; measurement of the electrical activity produced by skeletal muscles.
EOG	Electro-oculography; a technique for measuring the resting potential of the retina.
ESS	Epworth Sleepiness Scale
HMM	Hidden Markov model
HRV	Heart rate variability
ICA	Independent component analysis
IHR	Instantaneous heart rate

LOESS	Locally weighted scatterplot smoothing (LOcal regrESSion)
MAP	Maximum a posteriori
MSLT	Multiple Sleep Latency Test
NREM	Non-REM; deep sleep
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
REM	Rapid Eye Movements
SDANN	Standard deviation of 5 minute averages of R-R (N-N) intervals
SDNN	Standard deviation of all normal R-R (N-N) intervals during a 24-hour period
SWS	Slow-wave sleep

Foreword

> People say, “I’m going to sleep now,” as if it were nothing. But it’s really a bizarre activity. “For the next several hours, while the sun is gone, I’m going to become unconscious, temporarily losing command over everything I know and understand. When the sun returns, I will resume my life.”
>
> If you didn’t know what sleep was, and you had only seen it in a science fiction movie, you would think it was weird and tell all your friends about the movie you’d seen.
>
> “They had these people, you know? And they would walk around all day and be OK? And then, once a day, usually after dark, they would lie down on these special platforms and become unconscious. They would stop functioning almost completely, except deep in their minds they would have adventures and experiences that were completely impossible in real life. As they lay there, completely vulnerable to their enemies, their only movements were to occasionally shift from one position to another; or, if one of the ‘mind adventures’ got too real, they would sit up and scream and be glad they weren’t unconscious anymore. Then they would drink a lot of coffee.”
>
> So, next time you see someone sleeping, make believe you’re in a science fiction movie. And whisper, “The creature is regenerating itself.”
>
> – George Carlin [22]

This thesis was written at the Department of Information and Computer Science under the paternal guidance of D. Sc. (Tech.) Jaakko Hollmén and the supervision of Professor Olli Simula, to whom I extend my most sincere thanks. The work has been funded by the Finnish Centre of Excellence for Algorithmic Data Analysis Research (Algodan) as well as EIT ICT Labs, thematic area Health and Wellbeing.

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I would also like to thank the Trappist monks of Abbaye Notre-Dame de Scourmont for continuing to make the world a better place to live in.

Helsinki, 31 March 2013

Ola Rinta-Koski

Introduction

The importance of sleep quality often manifests itself when there is a disturbance: the lack of quality sleep has immediate consequences in the form of reduced daytime functionality, and long-term consequences affecting both mental and physical health. There is no doubt that sleep quality has a central role not only in the well-being of an individual, but also in the overall productivity of the work force, putting a monetary value on the health implications.

The goals of this thesis are twofold. The first goal is to present a literature review, giving an overview of sleep quality research, with particular emphasis on sleep quality assessment through automatic analysis of sleep signals. The second goal is to present a case study, giving examples of signal analysis within the framework of sleep quality.

This thesis is divided into three chapters. Chapter 1 gives an introduction to the subject of sleep, presents an overview of the structure of sleep, describes important sleep disorders, and introduces some of the methods used for acquiring sleep data through sensor input as well as their use in analysing sleep quality. Chapter 2 presents an overview of signal processing methods used in sleep quality assessment from sensor data. Chapter 3 deals with a case study using ballistocardiography to obtain sleep signals unobtrusively over a period of several months.

Chapter 1

Sleep and its Analysis

Most animals live according to a rhythm where periods of activity are interspersed with periods of reduced activity called *sleep*. Even fruit flies have been observed to enter a sleep-like state [55, 142]. Sleep can be distinguished from other states of reduced activity—anaesthesia, hibernation, or coma for example—by features such as rapid reversibility (a sleeping subject reverts to waking behaviour swiftly when awakened), recurrence, and spontaneity [143].

1.1 The purpose of sleep

> If sleep does not serve an absolutely vital function, then it is the biggest mistake the evolutionary process ever made.
>
> – Allan Rechtschaffen [128]

There are many theories concerning the purpose of sleep. Energy conservation and nervous system recuperation have been suggested as functions for deep (NREM) sleep [137], and brain activation occurring during REM sleep has been attributed to priming emotional, motor and sensory systems for action while the body is recuperating [58]. Differences in sleep behaviour across mammals may suggest that sleep serves different functions according to species [145], which may indicate that multiple evolutionary paths have independently resulted in the emergence of sleep [129].

1.2 Sleep disorders

Compromised sleep quality can lead to health issues, including psychiatric disorders such as depression, as well as subsequent increases in health care cost and productivity loss due to absenteeism [19] and diminished performance [52]. Sleep disturbances are a leading cause of diminished quality of life, often compounded by numerous side effects of pharmaceutical treatment [17]. Sleep disturbances associated with psychological stress have been associated with reduced immune response [62].

1.2.1 Sleep deprivation

Prolonged enforced sleep deprivation has been found to be eventually fatal for many animals [29]. Even in lesser amounts, continued lack of sleep increases "sleep pressure" and eventually the rebound is such that the onset of sleep can no longer be postponed [14].

In humans, sleep deprivation results in increased sleepiness, stress, and fatigue, as well as mood disturbances and decreased performance [38, 48, 66]. Habitually sleeping less than 6 hours per night has been found to decrease cognitive performance as much as total sleep deprivation for 2 nights [158]. Sleep deprived subjects often overestimate their cognitive capabilities and underestimate their sleepiness [11], which is a likely explanation for sleepy car drivers being at significantly increased risk of injury or death [31]. Sleep deprivation can also cause a marked reduction in immune system activity [104] and may be a causal factor in the development of reactive aggression and violence [67].

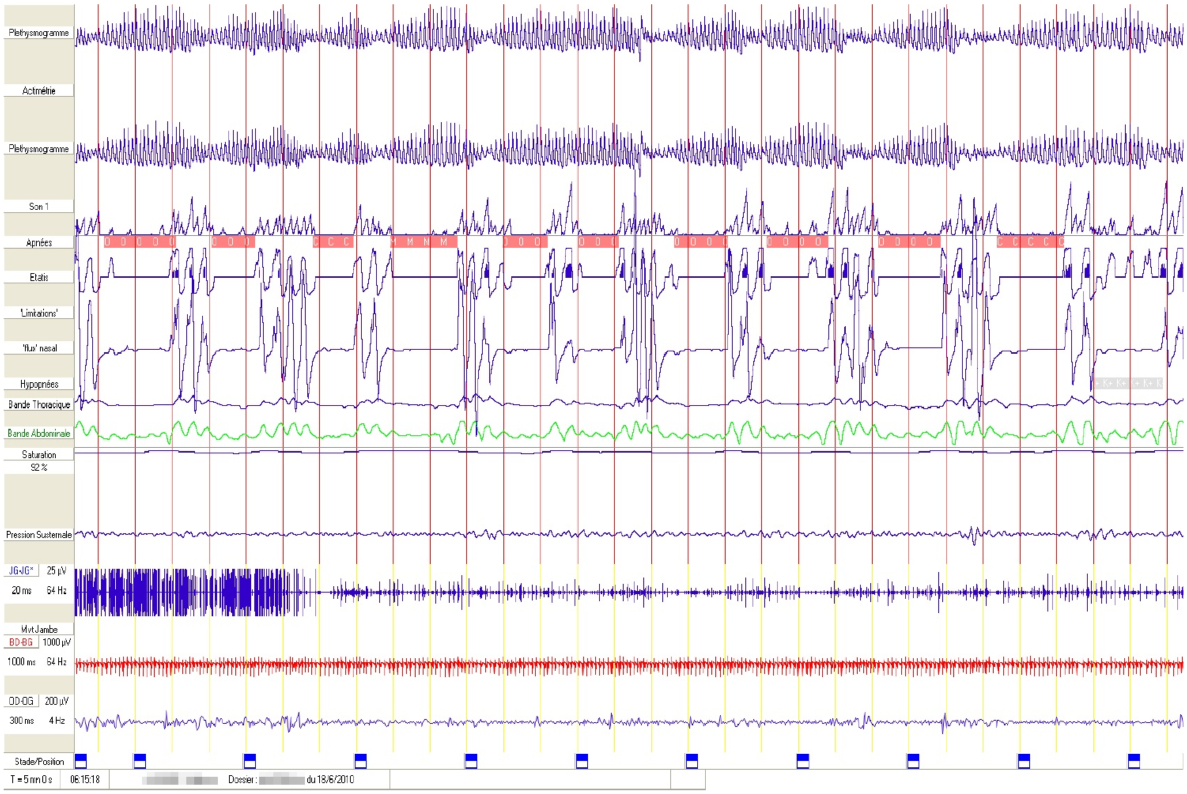

Figure 1.1: A 5-minute polysomnogram excerpt from a patient with sleep apnea. Cessation of breathing is indicated by periods of absence of nasal airflow (marked with red blocks).

1.2.2 Sleep apnea

Sleep apnea is a sleep disorder in which the patient stops breathing for a period while asleep (see Figure 1.1). It results in poor sleep quality and subsequent tiredness during the day. Erectile problems are common in men with sleep apnea, as well as loss of libido in women [57, 136, 169]. Sleep apnea is strongly associated with the risk of traffic accidents [150] and is a leading cause of excessive daytime sleepiness [109].

1.2.3 Insomnia

The term *insomnia* is used for a wide variety of sleep quality and quantity deficiencies. 10–30 percent of the adult population is affected by insomnia [80]. It is associated with numerous morbidities, including decreased quality of life, absenteeism, traffic accidents, loss of productivity [91], and increased general health care load [80]. Insomnia affects over 80% of patients suffering from major depression [114], and research suggests that insomnia, rather than depression, is the root cause [156].

1.2.4 Narcolepsy

Narcolepsy is a sleep disorder in which the patient has trouble staying awake during the day [162]. It can be associated with cataplexy (sudden loss of muscle tone) in which case it is the result of a genetic disorder [99, 112, 151]. There have been reports of increased occurrence of narcolepsy in children inoculated with the flu vaccine Pandemrix [7, 33, 119, 152], suggesting the need for further research in this field.[1]

1.3 Measuring sleep quality

While sleep quantity can be readily established by studying polysomnographic recordings, sleep quality is somewhat more ephemeric. In addition to total sleep time, features such as sleep onset latency [134], sleep fragmentation [105], time awake [41], and number of arousals [50, 105] have been used as qualitative measures; however, in some cases an individual may still experience non-refreshing sleep while having all of the above features comparable to normal individuals with no complaints [75].

Sleep quality, rather than quantity, has been found to be related to health, depression, fatigue, and overall satisfaction with life [123]. Automatic methods proposed for sleep quality assessment have used features such as sleep stage proportions [97, 103], number of arousals [105], roll-over movement detection [103], and so on.

1.3.1 Subjective assessment

Subjective sleep quality has traditionally been assessed using methods such as sleep diaries and questionnaires. These methods have their drawbacks, as their accuracy is subject to the individual's recall.

The Pittsburgh Sleep Quality Index (PSQI) [20] is a questionnaire for assessing subjective sleep quality. It measures seven features of sleep: subjective quality, latency, duration, habitual sleep efficiency, disturbances, use of medication, and daytime disfunction [85]. PSQI has been criticized for its inability to distinguish between sleep-related disturbances and general dissatisfaction, such as pessimistic thinking [47]. Its reflective quality also makes it less suitable for pediatric care.

The Epworth Sleepiness Scale (ESS) [63] is a simple list of 8 items, scored from 0 to 3, intended to measure the subject's likelihood of dozing off during common situations in daily life [19]. ESS is intended as a simpler alternative for the Multiple Sleep Latency Test (MSLT) [24], which involves monitoring and expert analysis similar to PSG. ESS scores of patients with sleep disorders are significantly correlated with MSLT sleep latencies [64].

1.3.2 Sleep of couples

The overwhelming majority of sleep studies has concentrated on studying a single subject. However, body movements of couples sharing a bed have been found to exhibit a strong relationship [118] and partner movements have been found to induce arousals from sleep [94]. The sleep quality of partners of sleep apnea patients is strongly influenced by the patient's condition [39, 157]. General relationship quality is also strongly correlated with sleep quality [155].

1.4 Sleep stages

Before the invention of electroencephalography (EEG), sleep was considered to be a homogeneous state. The discovery of distinct states of activity launched modern sleep research [83, 153]. Although the increasing accuracy of digital measurement devices has enabled adaptive methods of sleep signal analysis [5, 12], using discrete sleep stages as labels for periods of sleep remains a useful tool.

Sleep in mammals and birds is divided into two distinct phases [9].[2] REM, short for Rapid Eye Movements, is a state with a high level of brain activity accompanied by the characteristic ocular movement. Non-REM (NREM) sleep is a deeper sleep state, with markedly reduced brain activity. In addition, wakefulness can be labeled as a third sleep phase for ease of analysis.

Human sleep alternates between NREM sleep and REM sleep in roughly 90 minute cycles, starting with a cycle dominated by deep NREM sleep and turning into a cycle consisting mainly of light NREM sleep and REM sleep towards the end of the night [23, 163]. Sleep and sleep stage durations follow exponential distributions [28].

Various disorders may change the order and nature of sleep stages. For instance, narcolepsy patients typically enter REM sleep soon after sleep onset without cycling through NREM sleep stages [25, 162]. Patients with schizophrenia often have significantly reduced periods of slow-wave sleep [21].

1.4.1 Wakefulness (W)

Wakefulness can be characterised as the absence of both NREM and REM sleep. A human experiencing wakefulness is fully responsive and in command of his motor and cognitive faculties. Vital signs, such as pulse and breathing, are consistent with being awake. Eyes are generally open with functional vision. EEG recordings show a low amplitude high-frequency signal [133].

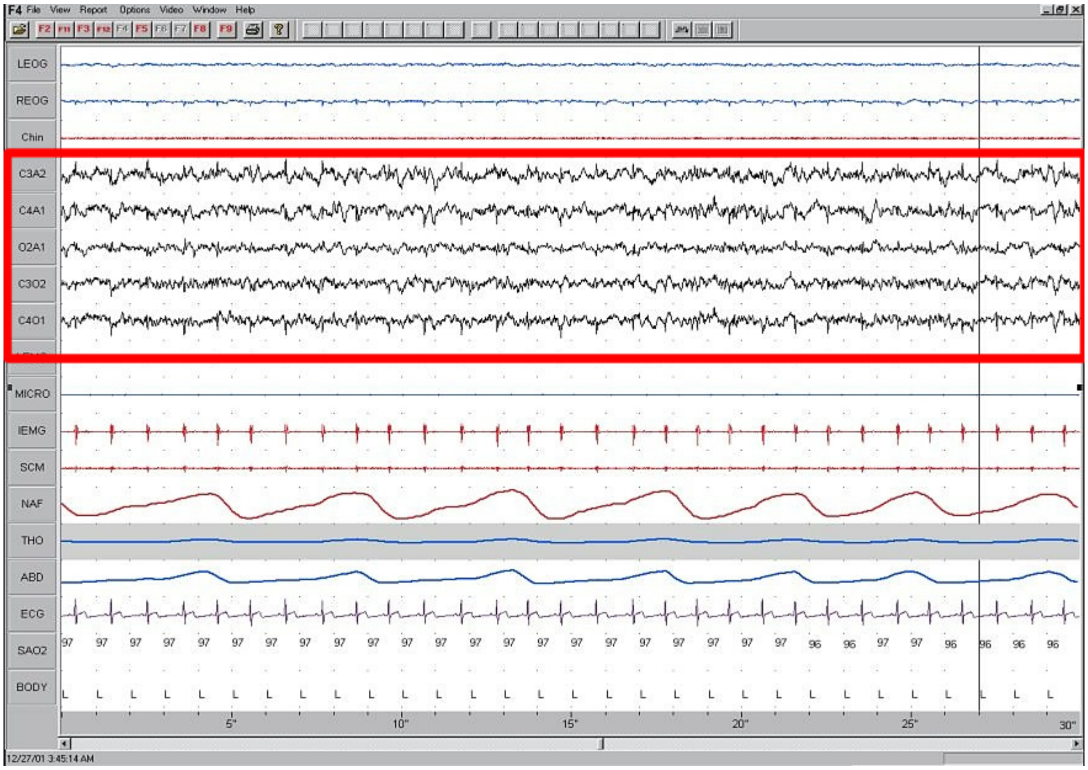

Figure 1.2: A 30 s polysomnogram excerpt from a patient in NREM stage N1. EEG electrode output highlighted.

1.4.2 NREM sleep (N1, N2, N3)

NREM, or deep sleep, is divided into three (previously four) distinct stages. Approximately 75% of sleep consists of NREM stages [23].

N1, also called light or transition sleep, is entered gradually from wakefulness with increased slowing of brain activity. Eyes are typically closed, and slow eye movements may be present. Figure 1.2 shows an example of a polysomnogram during N1.

N2 is characterised by two EEG patterns that mainly occur during this particular stage. *K-complexes* are the largest healthy EEG events [26], with voltage peaks in the hundred-millivolt range. They are often followed by *sleep spindles* (also called sigma waves), which are bursts of 12–14 Hz waves that last for at least 0.5 seconds. K-complexes are thought to occur spontaneously and to trigger sleep spindles and other cortical activity during NREM sleep [6].

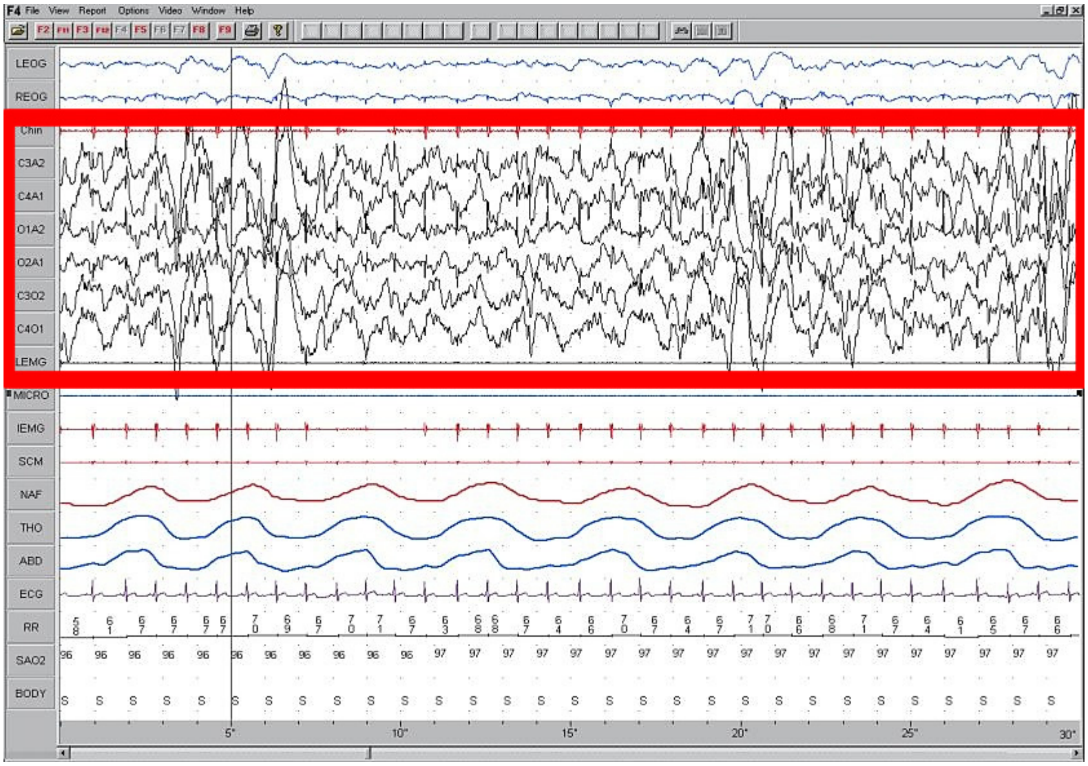

Figure 1.3: A 30 s polysomnogram excerpt from a patient in NREM stage N3 (stage 4 according to Rechtschaffen-Kales rules [130]). EEG electrode output highlighted.

N3, or slow-wave sleep (SWS), covers what was previously considered to be two distinct stages, with Stage 4 being more intense than Stage 3 [130], but recently published guidelines no longer make the distinction [61]. It is the deepest sleep stage and the hardest one to awake from. EEG activity is dominated by slow delta waves. Figure 1.3 shows an example of a polysomnogram during N3.

1.4.3 REM sleep (R)

REM sleep gets its name from the rapid eye movements that are a characteristic feature of this sleep stage.[3] Eyes are closed and move rapidly from side to side, occasionally in other directions. Brain activity is increased, so much so that it resembles brain activity during wakefulness, which is why REM sleep is also called *paradoxical sleep*.[4]

While the brain state in REM sleep resembles wakefulness, major muscular groups are paralysed and movement (other than ocular) is minimal. Blood pressure and heart rate are reduced [154]. Many male mammals have erections during REM sleep [57, 139].[5] Dreaming was initially thought to occur only during REM sleep, but in fact occurs during both REM and NREM stages [45, 111]. Dream recall is typically most vivid and frequent when waking up from REM sleep [129].

1.5 Monitoring sleep

Various physiological parameters can be monitored during sleep in order to gain insight into state changes within the sleeping test subject. These parameters include heart rate, central nervous system activity, respiration amplitude and frequency, muscular activity, and so on. The signal recordings can be used for e.g. sleep staging, detecting various disorders such as apnea, and other analysis applications.

1.5.1 Polysomnography

Polysomnography[6] (PSG) is a method for monitoring multiple physiological variables during sleep. It involves placing a number of electrodes on the body, then monitoring the output of these electrodes while the patient is asleep. A polysomnogram incorporates multiple channels of data, including EEG [44, 76], electrooculography (EOG) [161], electromyography (EMG) [84], and cardiorespiratory signals [131]. The actual number and selection of channels used for a particular polysomnographic recording depends on the disorder being diagnosed [77].

Polysomnography can be used in the diagnosis of a variety of sleep disorders. These include hypersomnias[7], such as sleep apnea [160] (Figure 1.5) and narcolepsy [82], various parasomnias[8] [138], and other sleep-related breathing disorders [77]. However, the diagnosis of insomnia does not generally indicate polysomnographic evaluation [80].

Figure 1.4: A pediatric patient prepared for a polysomnogram by a respiratory therapist.

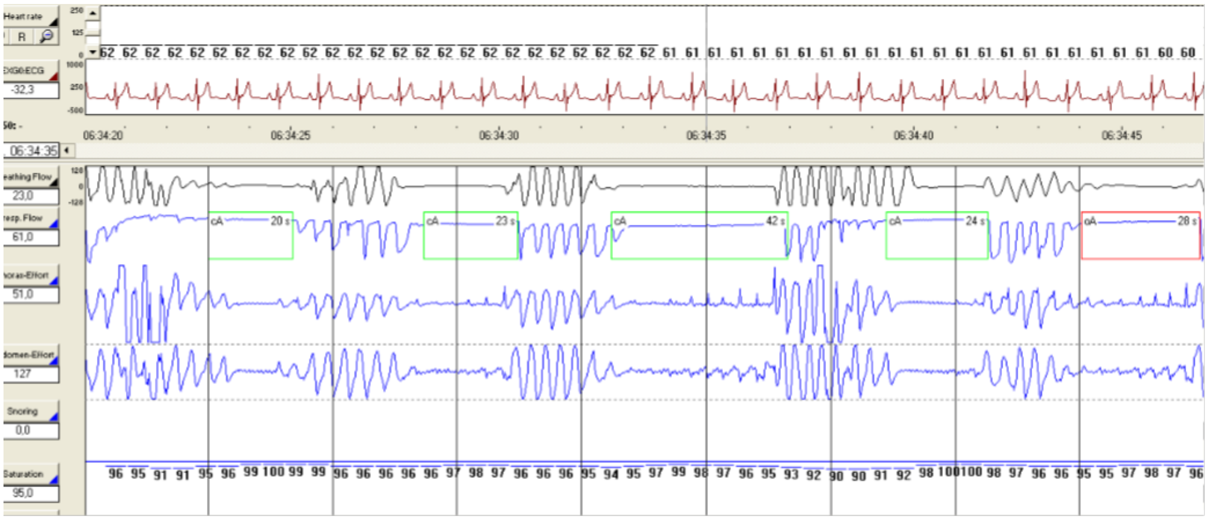

Figure 1.5: A polysomnogram of a patient with obstructive sleep apnea.

Polysomnograms are traditionally analysed using guidelines developed in the 1960s by Rechtschaffen and Kales [130]. PSGs are analysed in 30 second epochs.[9] If an epoch contains signs of more than one sleep stage, the stage with the longest duration wins, and the whole epoch is credited to that stage. This works fine for normal, healthy sleep, but presents problems when analysing disturbed sleep, as there may be a great number of stage changes within one epoch [8, 56]. Abnormal sleep in general can present problems to the expert analysing the PSG recording within the Rechtschaffen-Kales framework. Especially in the case of obstructive sleep apnea, interscorer agreement can vary significantly [147].

While PSG is universally accepted as the clinical standard for sleep scoring, it is less well suited to non-clinical settings. Patients actually tend to prefer the sleep laboratory when it comes to PSG [46, 125]. Reasons vary from perceived quality of the recording to problems with the electrodes staying in their intended location on the body. Any possible cost savings may also be offset by having to repeat the PSG when the output is not of sufficient quality [102]. Having to wear electrodes on the body (Figure 1.4) is also far from ideal for long-term tracking of sleep; while the electrodes are fairly well tolerated in the context of a brief hospital stay, it's not feasible to ask patients to wear them indefinitely.

1.5.2 Actigraphy

Activity-based monitoring, or actigraphy, is used in sleep research to infer sleep patterns from body movement data. Acceleration sensors are typically worn on the wrist [81], but also elsewhere on the body such as the jaw [140], the ankle/calf [95][10] or around the torso [165], and movement (or lack thereof) is used to determine activity patterns.

Due to the need to differentiate between rest and activity, actigraphy can not be used for patients with motor disorders or otherwise abnormal nocturnal motility [135]. Actigraphy tends to overestimate sleep, because distinguishing between sleep and rest

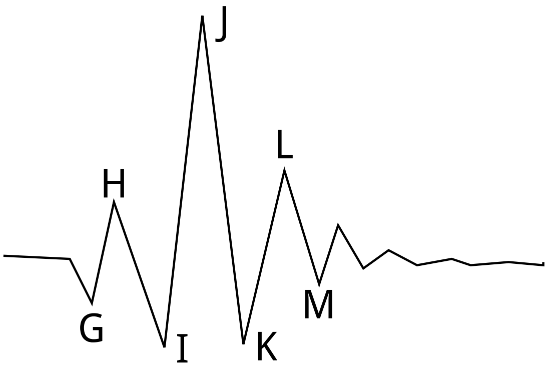

Figure 1.6: BCG waves in a single heartbeat. H through K is the systolic phase.

while awake is difficult, and it may not provide prediction values that are accurate enough [68, 124].

Mobile phones with acceleration sensors can be used as sleep stage sensitive alarm clocks with actigraphy-based software [74], although their accuracy in this application has not been yet scientifically verified. The accuracy with regard to sleep parameters such as total sleep time and sleep efficiency is comparable with dedicated actigraphy devices [108].

1.5.3 Ballistocardiography

Ballistocardiography (BCG) is a method for detecting heartbeat and respiration based on the body movement induced by the heart's pumping action. Recent developments in signal processing and sensor technology have made it possible to use BCG in conjunction with special furniture for completely unobtrusive measurements [3, 117]. BCG has also been used in non-sleep-related cardiovascular research [40].

BCG waves can be divided in three groups: pre-systolic (F, G), systolic (H, I, J, K), and diastolic (L, M, N, etc.). Non-systolic waves are often obscured by interference from other waves, posture changes, and so on, which leaves the systolic wave complex (Figure 1.6) as the best candidate for detection. This corresponds to the QRS complex in ECG recordings (see Section 2.1).

1.5.4 Interferometry

Interferometry, using either millimeter wave [100, 101] or laser [53] diodes, can be used for non-contact monitoring of respiration and heart rate. Minute variations in chest displacement can be measured and post-processed in a similar manner to BCG.

Chapter 2

Signal Processing of Sleep Recordings

Physiological signals recorded during sleep have to be further processed to find relevant information within the data. By reducing the dimensionality of multiple channel input, relevant features can be extracted. For instance, the raw waveforms obtained from ECG or BCG recordings have to be analysed in order to locate the heartbeats contained within the signal before further heart rate analysis can be done.

2.1 Heart rate detection

Heart rate can be detected using ECG by locating the QRS complex (Figure 2.1) within each heartbeat and calculating the peak-to-peak interval. BCG heart rate detection can be done in a similar manner using the HIJK systolic waves [87].

Difficulties in QRS detection vary from significant variations in the input waveform to artifacts such as electrode motion, muscle noise, and false positives from P and/or T waves [148]. Since respiration distorts heartbeat waveforms, pulse oximetry data, if available, can be used to improve heart rate detection [149].

Approaches for automatic QRS detection include using neural networks [59], wavelets [10, 65], Hilbert transform [15], MAP (maximum a posteriori) estimation [18], counting

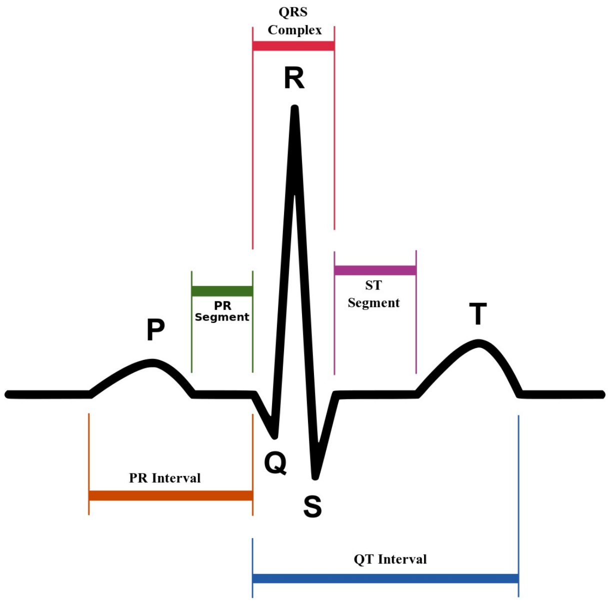

Figure 2.1: Schematic diagram of normal human heart sinus rhythm as seen on ECG.

zero crossings [72], and hybrids of the above [168]. Wavelet transformation [90] can be used to decompose waveforms related to respiration and pulse [27].

Heart rate can also be detected from the frequency transform of the signal by finding a peak corresponding to the heart rate. This method is more tolerant of heart rate variability caused by arrhythmias and respiration [115].

2.1.1 Heart rate variability

Heart rate variability (HRV)—fluctuations in beat-to-beat intervals—is an indication of autonomic nervous system activity and a key indicator of an individual's cardiovascular condition [30]. HRV decreases under stress and increases with rest [35, 51]. Low HRV indicates higher risk of death in heart disease patients and elderly subjects and higher risk of coronary heart disease in the general population [35, 113].

HRV can be quantified by various methods, including time domain and frequency domain [146] as well as geometric and nonlinear methods [70]. HRV is measured in the time domain by looking at the variation of the intervals between adjacent QRS complexes, also known as normal-to-normal (N-N) intervals [89].

The most commonly used time domain HRV measure is SDNN, the standard deviation of all N-N intervals in a 24 hour period. Abnormalities such as ectopic and missed beats need to be edited out of the ECG recording for accurate clinical analysis, otherwise these events will artificially increase SDNN [70]. Clinical laboratories usually require at least 18 hours of usable data in a 24 hour ECG recording for SDNN analysis [70]. HRV measures obtained from sleep BCG recordings without annotations are therefore not directly comparable with those obtained from ECG recordings, as anomalies have not been excluded and also because HRV measures obtained from recordings of different durations should not be compared [89].

2.2 Respiration detection

A BCG or a pulse oximetry [92] recording can be used for respiration detection. The respiratory component, compared to the heartbeat component and noise, has the following characteristics: lower frequency, smoother transitions, and greater amplitude [54]. Preprocessing involves low-pass filtering so that the heartbeat components are discarded.

Respiration can also be detected from video recordings using independent component analysis [43] or thermal infrared images using wavelet analysis [107].

Respiration rate variation is highest when awake or in REM sleep, and lowest in deep sleep [116]. Thus, respiration variability can be used as a parameter in sleep staging.

Cheyne-Stokes respiration (CSR), a breathing disorder resulting from instability of the respiratory control system, is common in patients with heart failure [166]. It can be detected by observing respiration amplitude and looking for signs of the typical waning-waxing pattern associated with CSR [127].

Respiration amplitude can be used to detect the onset of sleep bruxism [69].

2.3 Sleep staging

Sleep staging involves labeling periods of sleep according to patterns in measured biosignals. In PSG, this is traditionally done by hand. Due to hand-scoring being an empirical rather than a rule-dependent process, agreement between PSG experts can vary significantly [147]. On the other hand, a rule-based staging system always glosses over the physiological heterogeneity of sleep stages [106].

Automated methods for sleep staging from PSG recordings have been developed, using either the full PSG recording [2] or a subset of PSG channels, optionally adding data from other channels such as actigraphy [36]. Analysis approaches include looking at sleep spindle distributions [37], upper airway impedance [132], etc.

Hidden Markov models (HMMs) [126] use state observation and transition probabilities to model a time series; the current state determines the likelihood of the following state. This makes HMMs a particularly suitable candidate for automated sleep staging, as the possible stage transitions are highly dependent on the prevailing sleep stage.

2.4 Apnea detection

Apneic episodes are pauses in respiration. Detecting apnea from BCG recordings involves separating the respiratory signal, then classifying intervals within the signal. Alternatively, oxygen saturation [159, 167], heart rate variability [32, 93, 141], or acceleration sensors placed directly on the body [34] can be used.

Chapter 3

Case Study: Ballistocardiography and Sleep Analysis

The final part of the thesis presents a case study, using signals obtained using BCG to analyse sleep over a period of several months. BCG is particularly suitable for long-term monitoring of sleep, as the sensors can be placed in the bed without the need for direct contact between the sensor and the sleeper, making the monitoring equipment completely unobtrusive.

3.1 Data acquisition

Measurements were made using a BCG-based device from Beddit (`www.beddit.com`). The device uses piezoelectric pressure sensors (one per sleeper, up to two) to detect sleeper movement. Data from the pressure sensors is digitized into 16-bit unsigned integer form at 140 Hz, with actual device resolution of 12 bits per channel.

Measurements of two test subjects, a male and a female in the 40. . . 45 year age bracket, were collected over a 10-month period. Test subjects had no history of diagnosed sleep disorders.

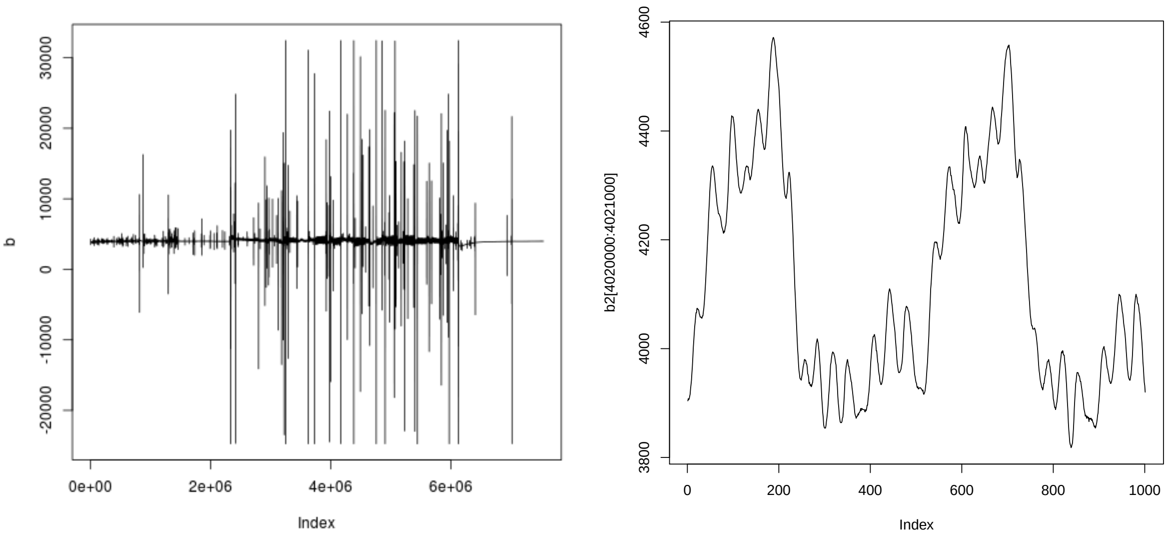

Figure 3.1: BCG output, single channel (sleeper 1, 12 November 2012). Elapsed time (in seconds) is on the X axis. The output of the BCG sensor (relative force exerted by the movement of the sleeper) is on the Y axis.

Figure 3.1 shows the raw BCG output for a single sleeper. On the left is a graph of the whole night. Spikes in the waveform are caused by bodily movement, such as posture changes. While the sleeper is moving, vital signs such as respiration and heart rate can not be observed, as the pressure sensor can not pick up these far weaker signals which are being masked by the movement. On the right is a zoomed portion, 1000 samples long, showing two respiration cycles. Movement induced by heartbeat is superimposed on the larger waveforms induced by respiration.

3.2 Prior information

Looking at the BCG signal from a sleep quality point of view, the signal has three main extractable features: body movement (e.g. posture changes), respiration, and heartbeat. All of these are relatively slow; respiration and heartbeat have typical respective frequency ranges of $0.1 \ldots 0.5$ Hz and $0.7 \ldots 1.8$ Hz [164].

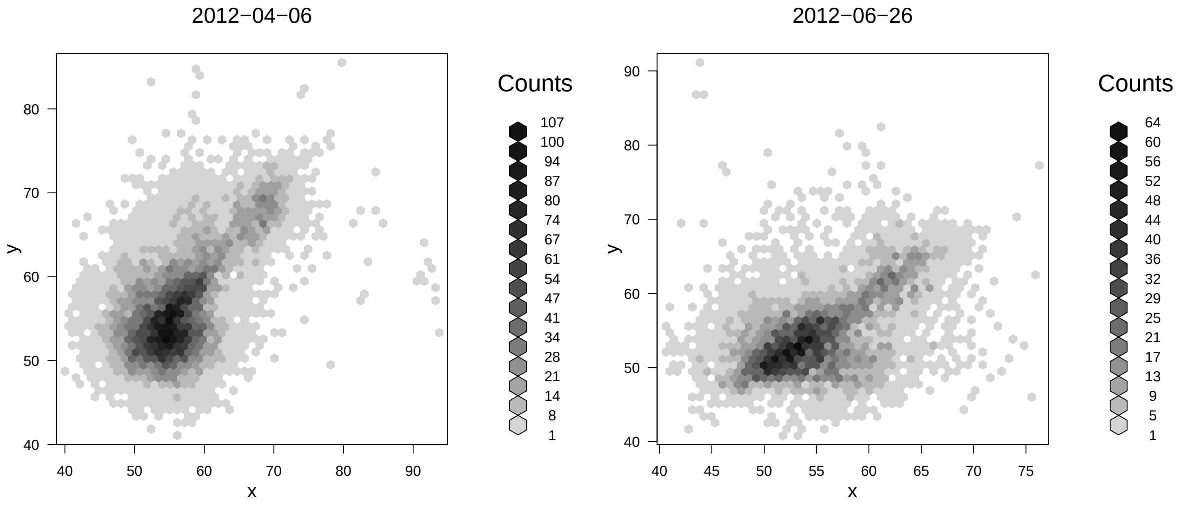

Figure 3.2: Instantaneous heart rate correlation between sleepers 1 and 2 for 6 April 2012 and 26 June 2012.

3.2.1 Heart rate

Heart rate is presented in the output of the Beddit device as instantaneous heart rate for each heartbeat. Individual heartbeats are labeled with a timestamp. The output consists of pairs of timestamps and their associated instantaneous heart rate values. Timestamps are presented with subsecond accuracy. These were rounded down to the nearest second for ease of analysis.

3.3 Instantaneous heart rate

Instantaneous heart rate (IHR) is the beats-per-minute rate computed from the interval between two single heartbeats [13]. Figure 3.2 shows the instantaneous heart rates of both sleepers plotted against each other. The observations are matched by timestamp. The scatterplots show a correlation, as quite a few observations fall on the diagonal. A similar sleep-wake rhythm may be part of the explanation, in combination with the strong correlation between bed partners' movements [118].

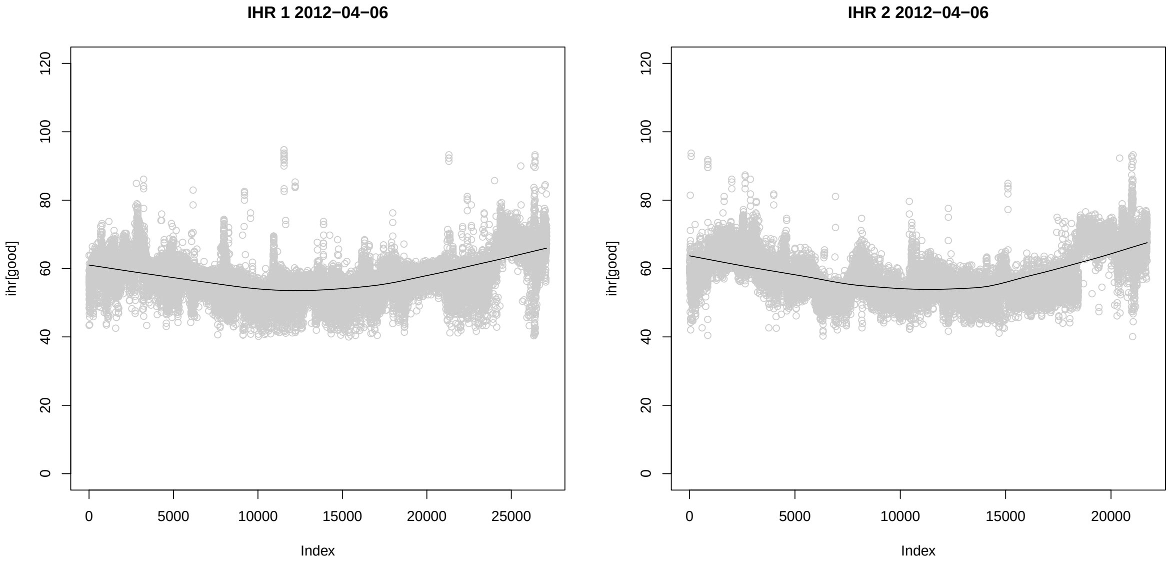

Figure 3.3: Instantaneous heart rate for sleepers 1 and 2, 6 April 2012.

Figure 3.3 shows two scatterplots of instantaneous heart rate over the course of a whole night. Sleeper 1 is shown on the left, Sleeper 2 on the right. The LOESS curve (in black) shows how the average heart rate first decreases, then increases as the night progresses. The initial decrease is the result of deeper relaxation with deepening sleep. The increase towards the morning is the result of an increase in the time spent in REM sleep, where the heart rate is higher than in NREM sleep [121].

3.4 Respiration

Respiratory rate and amplitude can be used for sleep staging, but also for detecting various disorders. Abnormal respiratory rate and pattern during sleep is prevalent in various sleep apneas [110, 122], but may also indicate brain stem lesions [78], upper airway resistance syndrome [49], breathing disorders associated with heart failure [166], and so on. The occurrence of respiratory disturbances increases naturally with age [120], which should be taken into account when analysing the measurements.

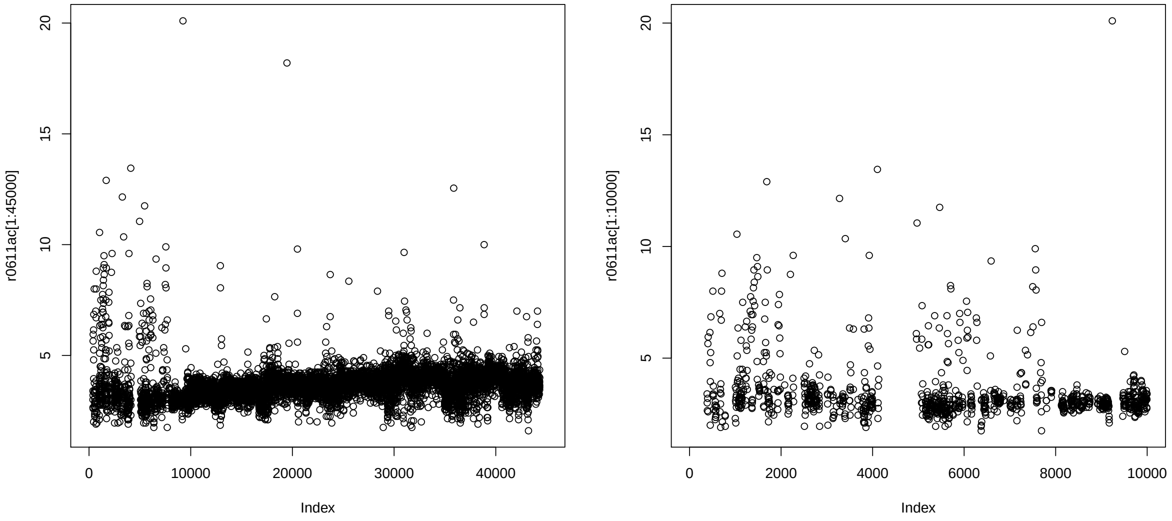

Figure 3.4: Respiratory cycle length for sleeper 1, 6 November 2012. A close-up of the beginning of the recording shown on the right.

Figure 3.4 shows a typical recording of respiratory cycle lengths for a single night. As can be seen from the plots, the beginning of the recording shows a large number of long ($> 5s$) cycles. At around 8000 samples into the recording, the number of long cycles decreases noticeably. This most likely indicates that the sleeper has been present in the bed but not sleeping, and that the change in respiratory pattern coincides with sleep onset. The gap at around 5000 samples is likely to correlate with the test subject getting up to brush his or her teeth before finally tucking in for the night.

Figure 3.5 shows the respiration amplitude of sleepers 1 and 2 during one night. The plots are smoothed by taking the moving average of 100 observations. Periods of higher activity are interspersed with periods of lower activity, suggesting a relationship between respiration amplitude and sleep stages, which is indeed the case [61, 130].

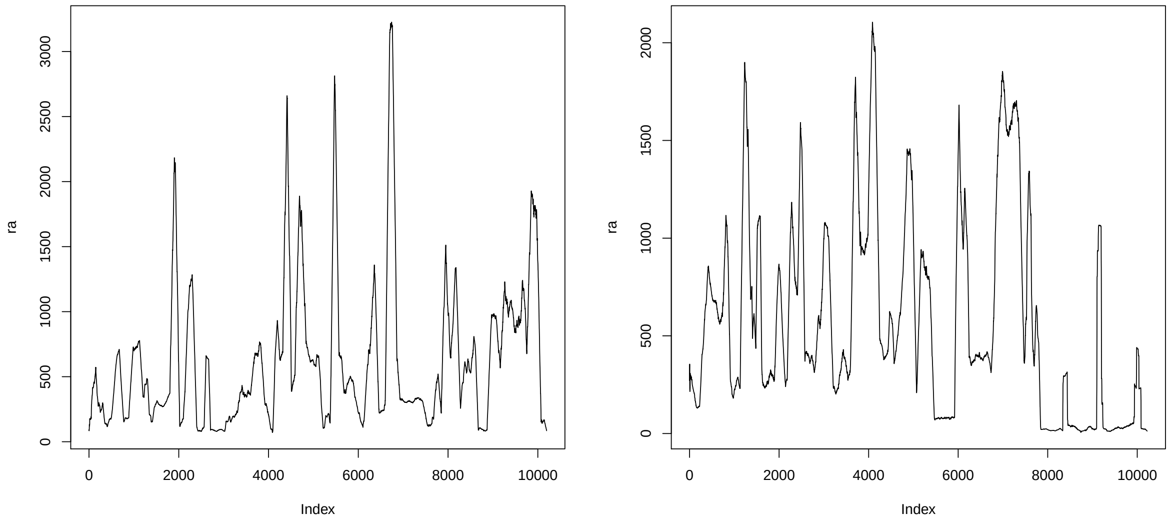

Figure 3.5: Respiration amplitude: moving average of 100 observations, sleepers 1 and 2, 6 April 2012.

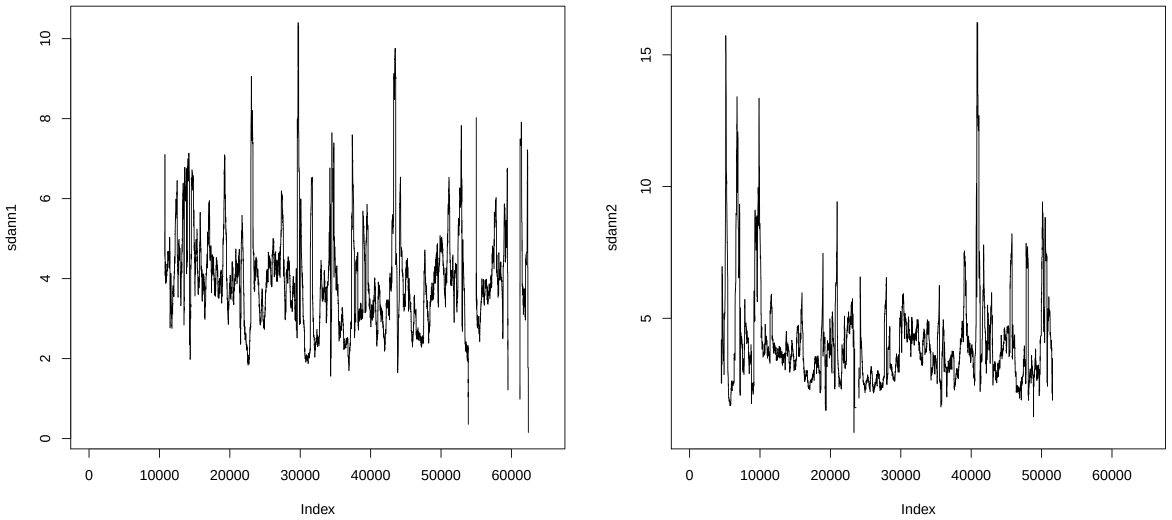

Figure 3.6: SDANN for sleepers 1 and 2, 9 April 2012.

3.5 Heart rate variability

The most commonly used time domain measure of HRV is SDNN, the standard deviation of all normal heartbeat intervals [70]. Normal heartbeat intervals are obtained from ECG R-R intervals by discarding anomalies such as ectopic beats (N stands for “normal”). Another HRV time domain measure is SDANN, which is the standard deviation of 5 minute averages of heartbeat intervals. SDANN is more robust in handling anomalies in the measurement data.

The BCG data used here was not preprocessed for normal heartbeat intervals, so measurements shown here are not directly comparable with those obtained from annotated ECG recordings. Figure 3.6 shows SDANN for both sleepers during the course of one night.

3.5.1 Poincaré plot

A Poincaré plot, also called a *first return map*, plots a time series against itself delayed by one interval. The shape of the plot can be used to assess cardiovascular health; patients with ventricular tachyarrhythmias give plots with shapes resembling a ball or a torpedo, whereas healthy subjects give plots in the shape of a fan or a club [60].

Poincaré plots are normally used in cardiovascular analysis with R-R intervals. However, as this data was not available, instantaneous heart rate was used instead. As instantaneous heart rate is the inverse of R-R interval length, the plot direction is reversed: observations made on healthy subjects exhibit a fan- or club-shaped pattern with the head close to the origin instead of farthest from the origin. Figure 3.7 shows Poincaré plots for both test subjects for the night of 6 April 2012. Without attempting a real clinical analysis, it can be seen that both plots exhibit a club-shaped pattern, which is typical of subjects in good cardiovascular health.

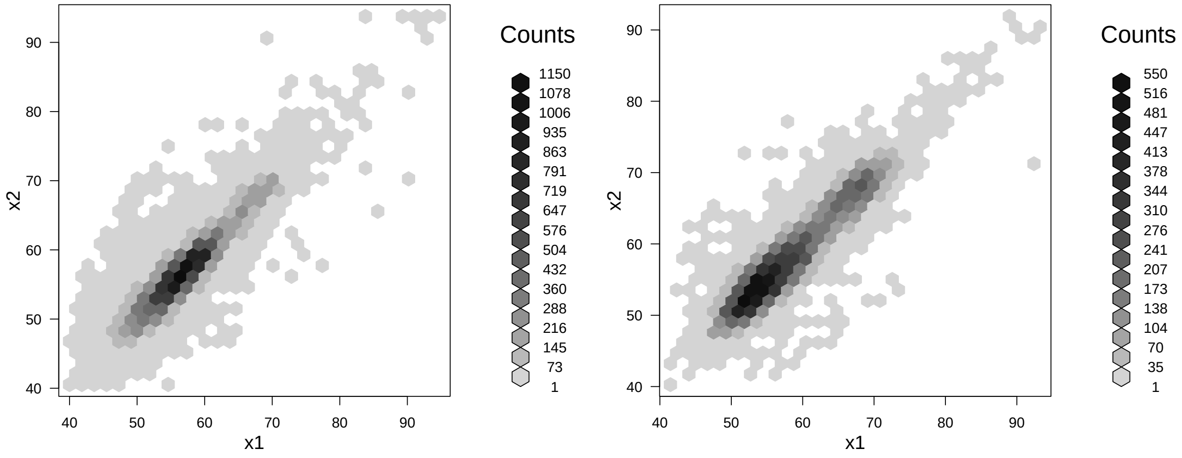

Figure 3.7: Poincaré plot, sleepers 1 and 2, 6 April 2012.

Chapter 4

Summary and Conclusions

This thesis provides an overview of sleep quality research using non-invasive sensors. Different methods of using sensor input to gather sleep data are explained and their relationship with traditional methods predating modern data analysis techniques is discussed. The use of non-invasive sensors for making continuous sleep recordings in the home is demonstrated using a sensor device equipped with pressure-sensitive piezo sensors providing ballistocardiographic data. This one-dimensional signal, outputting a single pressure differential value at each sample cycle, is further processed to show vital signs such as pulse and respiration rate and amplitude. This post-processed data is then studied in a descriptive manner.

The quality of sleep is an extremely important factor in the quality of life in general. Sleep quality problems can indicate implicated in a large number of disorders, both physiological and psychological. Intelligent methods can be used to aid in sleep quality assessment through the monitoring and automatic analysis of physiological signals.

4.1 Directions for future work

The device used for the sleep recordings provides, through the use of the Beddit web service, a rudimentary analysis of sleep patterns. This could be combined with other data channels available from the device (not only BCG but also illumination, noise etc.) as well as additional modalities, such as video recordings (perhaps using infrared light).

Sleep staging was beyond the scope of this work, but has been done with similar bed sensors [73, 96, 98]. Reliable sleep apnea detection, perhaps combined with a method to interrupt the apneic episode by arousing the sleeper, would also be a useful application, and there is precedent for this kind of work as well [4, 86, 116].

While sleep research in a clinical setting has been going on for decades, it is only through the development of modern signal processing methods that long-term, unintrusive monitoring of sleep has been made possible. This opens new possibilities for research, such as the so far little studied interaction of two sleepers sharing a bed and e.g. the development of their sleep patterns as the subjects age and their relationship matures.

4.2 Test setup thoughts

There were some reliability issues with the equipment. No measurements were made on nights when the head unit was powered off due to a disconnected power cord. Occasionally measurements were stored even with no sleepers present. These “ghost measurements” were easy enough to detect in post-processing, however, the need to do so required adding another post-processing phase. Nights on which only one sleeper was present, but two data sets were recorded, are more difficult to detect, although this could be done with appropriate post-processing. In this work, data for nights for which the presence of both sleepers could not be confirmed was not used.

The significant crosstalk between the two sensor strips was removed to some extent by the server software. The accuracy of this filtering was not assessed, so it is difficult to say whether the crosstalk removal was successful. What is known is that the sensors performed best when sleeper movement was minimized, in other words, when both test subjects were simultaneously in a deep sleep phase. This means that breath and heart rate analysis within deep sleep was probably quite accurate, whereas the analysis of movement cross correlation was probably less so.

Notes

[1] As of October 2012, the European Medicines Agency does not consider the evidence presented so far to be conclusive [42]. Pandemrix is a trademark of GlaxoSmithKline.

[2] While separate REM and NREM sleep states have been observed in many animals, there are also exceptions, notably monotremes such as the platypus [79] and the echidna [144], in which sleep consists of a single state with both REM and NREM characteristics.

[3] Sleep disorders such as narcolepsy may involve states which have features from both REM and NREM sleep [88]. An example would be the simultaneous presence of eye movement and sleep spindles.

[4] REM sleep has also been observed in animals which do not move their eyes [16], so perhaps another name would be more appropriate.

[5] Many common features of mammalian sleep do not apply across the board, and so it is in this case as well; the armadillo only has erections during deep sleep [1].

[6] Derived from Greek and Latin: *"polus"* (Greek: many), *"somnus"* (Latin: sleep), *"graphein"* (Greek: to write)

[7] Hypersomnias are sleep disorders where the patient is excessively sleepy and is not refreshed by sleep. The most common cause of hypersomnia is voluntary sleep deprivation [88].

[8] Parasomnias are sleep disorders involving abnormal physical and/or mental behaviour or experiences during sleep [88].

[9] A plotter running at a paper speed of 10 mm/s gets through one page in 30 seconds.

[10] Actigraph placement on the ankle/calf is recommended for infants and toddlers [134].

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Index

Colophon

This thesis was written between February 2012 and March 2013 on computers running Ubuntu Linux, using the following software:

- LyX 2.1.0dev — word processing, `http://www.lyx.org/`
- pdflatex, TeX Live 2012 — typesetting, `http://www.tug.org/texlive/`
- Mendeley 1.8.2 — bibliography manager, `http://www.mendeley.com/`
- R version 2.15.1 — programming, graphics, `http://www.r-project.org/`
- Inkscape 0.48 — graphics, `http://www.inkscape.org/`
- git — distributed version control, `http://git-scm.com/`

The typeface is Latin Modern Roman, which is a version of Computer Modern Roman, the timeless classic by Donald E. Knuth [71]. Normal text is typeset at 12 pt size.