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Sleepmonitoring for Congestive Heart Failure Patients

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«Gratitude is the memory of the heart»

Jean Baptiste Massillon

In this spirit, I would like to take the opportunity and to thank everyone who has played a significant role in the development of this Master Thesis.

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Zusammenfassung

Die Kombination von standardisierten Fragebögen und von Patienten erfassten Vitalparametern bietet einen neuen Ansatz zur kontinuierlichen Risikobewertung des Gesundheitszustandes des Patienten. Durch die Beantwortung von spezifischen Fragen nach einem speziellen Zeitschema erhält man eine kontinuierliche Risikobewertung, der sogenannte *Rolling Score*. Eine Machbarkeitsstudie wurde an zehn gesunden Probanden durchgeführt, welche mit einer mHealth Applikation und einem Smartphone ausgestattet wurden. Die Ergebnisse bestätigen die technische Machbarkeit des Konzepts und die *Rolling Scores* zeigen geringe Abweichungen zu den standardisierten Fragebögen ($< 8\%$). Weitere Studien sind für eine Verifikation des *Rolling Score* jedoch notwendig.

Schlagwörter: Risikobewertung, Screening, Fragebögen, ePRO, Telemedizin

Abstract

Combining standardized questionnaires and electronic patient-reported outcome to continually score individuals' health state, provides a new concept for risk assessment. Assigning a specific *Time Schedule* to each question results in a movement of the questionnaires' score over time, the *Rolling Score*. Ten healthy volunteers participated in a feasibility study and were equipped with a mHealth application on a smartphone. Results show the feasibility of the concept and the *Rolling Scores* have only small deviations compared to the standardized questionnaires ($< 8\%$). However, further studies are required for verification.

key words: Risk assessment, screening, questionnaires, ePRO, telehealth

«Imagination is more important than knowledge,

because knowledge is limited»

Albert Einstein

Contents

Parts of this work have already been published.

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List of Abbreviations

CHF	Congestive Heart Failure
SDB	Sleep Disordered Breathing
OSA	Obstructive Sleep Apnea
BQ	Berlin Questionnaire
STOP-BANG	STOP-BANG Questionnaire
PSQI	Pittsburgh Sleep Quality Index
ePRO	electronic patient-reportet outcome
apps	Applications
ICT	Information and Communication Technologies
KIT	Keep-in-Touch
NFC	Near-Field Communication
SRBD	Sleep-related Breathing Disorders
AASM	American Association of Sleep Medicine
AHI	Apnea and/or Hypopnea Index
CSB	Cheyne-Stokes Breathing
ICD	International Classification of Diseases
CSA	Central Sleep Apnea
BMI	Body Mass Index
RS	*Rolling Score*
Q	*Questionnaire*
C	*Category*
I	*Item*
GS	Global Score

CS	Category Score
IS	Item Score
$\tilde{C}$	*Rolling Score Category*
$\tilde{I}$	*Rolling Score Item*
mSR	*maximum Score Range*
POS	*Part of Speech*
BoW	*Bag of Words*
AHIT	*Assistive Healthcare Information Technology*
DSS	*Department Digital Safety & Security*
API	*Application Programming Interface*
URL	*Uniform Resource Identifier*
JSON	*JavaScript Object Notation*

1. Introduction

Applying mobile health applications to continually monitor patients becomes more and more present for individual management of patients with congestive heart failure (CHF) [1], [2]. One contributing factor to the excess morbidity and mortality in CHF population is sleep disordered breathing (SDB) [3]. Obstructive sleep apnea (OSA), a common type of SDB, has an estimated prevalence rate of 26 percent among American adults between the ages of 30 and 70 years [4].

Overnight polysomnography is the gold standard for diagnosing SDB, an expensive and time-consuming diagnostic method with limited capacity for testing in regards to the high number of patients [5]. Standardized screening questionnaires provide a concise, reliable and cost-effective method for rapid risk assessment of individuals' health state.

Validated and brief screening questionnaires like the Berlin Questionnaire (BQ) [6] and the STOP-BANG Questionnaire [7] can reliably identify persons in a community showing a high risk for OSA. Additionally, the quality of sleep can be assessed by the Pittsburgh Sleep Quality Index (PSQI), a self-reported questionnaire [8].

Using self-reported screening questionnaires and assigning a specific *Time*

Schedule to each question results in a movement of the questionnaires' score over time. This "Rolling Score" reflects the individual health state of patients up-to-date and can be applied to continually assess risk of patients easily by electronic patient-reported outcome (ePRO) approaches like mobile health based telemonitoring.

The present thesis deals with a new approach in risk assessment called *Rolling Score Concept* applying standardized questionnaires to continually score individuals' health state [9]. In addition to the presentation of the concept, a feasibility study on the risk assessment method in the field of sleep medicine has been conducted.

This chapter introduces the medical indication for this new risk assessment method and presents in detail the linkage between SDB and CHF as well as established screening methods for sleep apnea. Finally, definition of the Master Thesis' aim is described.

1.1. Mobile Health - Beyond Traditional Care

The present clinical care model for congestive heart failure is not optimal for improvement of chronic disease outcomes due to episodic hospitalization and de-hospitalization of CHF patients. The ready supply of mobile communication devices provide an opportunity to expand patient management beyond the traditional clinical model - an approach termed as mobile Health or mHealth [10]. Mobile applications ('apps') offer a new way to monitor patients at home, supporting transfer efficiency of measured physiological data and improvement of patients' compliance with the medical therapy. As

mHealth implies transmission of patients' vital signs using the internet and modern communication technologies, report of data is done by the patient himself - an approach referred to as electronic patient-reported outcome (ePRO) [11].

The provision of this health information to physicians is performed through telemedicine services. The „Bundesministerium für Gesundheit "defines telemedicine as the supply or support of health services by means of information and communication technologies (ICT), whereby patients and healthcare provider (physicians, pharmacies, hospitals and nursing assistance) or two healthcare providers are not physically together [12]. Telemonitoring as an application of telemedicine is defined as the remote medical surveillance of the health status from patients. The main application areas of telemedicine sevices are chronic diseases such as cardiovascular diseases and diabetes [12]. Telemonitoring concepts such as the Keep-in-Touch (KIT) System of the AIT Austrian Institute of Technology, support reliable and efficient data transmission using Near-Field Communication (NFC)-enabled smartphones and medical devices [13].

1.2. Sleep Apnea in Congestive Heart Failure

Sleep-related breathing disorders (SRBD) are identified as the most common co-morbidity in patients with CHF, occurring in almost half of the patients [14]. Consequently, SRBD are important contributors for the development and progression of heart failure and other cardiovascular diseases. It should be noted that only aspects referring to adult forms of the respective disorders

are dealt with and presented in this work due to different methods of diagnosis for pediatric forms.

1.2.1. Congestive Heart Failure

Congestive heart failure is the term used to describe the inability of the heart to provide the body's organs and tissues with sufficient oxygen at rest or under stress conditions (pathophysiological definition). This condition is based on a considerably reduced cardiac contractility. The clinical appearance of CHF is basically caused by a cardiac dysfunction and characterised by specific symptoms (fast tiredness, fluid retention, dyspnoea, heart palpitations) [15].

1.2.2. Sleep-related Breathing Disorders

The American Academy of Sleep Medicine (AASM) defines the following terms concerning SRBD [16]:

- **Apnea**: In adults, apnea events are defined as a drop in the peak signal of airflow by $\geq$ 90% of baseline for 10 seconds or more

- **Hypopnea**: In adults, hypopnea events are defined as a drop in the peak signal of airflow by $\geq$ 30% for 10 seconds or more associated with either an arousal or 3% or more arterial oxygene desaturation

- **Apnoa and/or hypopnea index (AHI)**: Is defined as the sum of apneas plus hypopneas per hour of sleep.

- **Cheyne-Stokes breathing (CSB)**: A specific periodic breathing form occurring in central sleep apnea and showing a crescendo-decrescendo pattern of ventilation that culminates in an apnea or hypopnea.

SRBD are «characterized by cycles of significant pauses in breathing and partial neurological arousals that ultimately have an impact on sleep quality and overall health» [3] The AASM estimates that sleep apnea, the most common type of SDB in CHF populations, is present in 26% of adults between the ages of 30 and 70 years [4]. According to the latest version of the International Classification of Diseases (ICD-10) block G47.3 [17], SRBD are broadly classified into two groups:

Obstructive Sleep Apnea

«Obstructive sleep apnea in adults is characterized by repetitive episodes of cessation of breathing (apneas) or partial upper airway obstruction (hypopneas). These events are often associated with reduced blood oxygen saturation.» [18]. The degree of severity is determined by the AHI, with a value of 5 or more required for diagnosis. It has been proposed to include OSA as an independent risk factor for cardiovascular diseases [19].

Central Sleep Apnea

«Primary central sleep apnea is a disorder of unknown cause characteri-

zed by recurrent episodes of cessation of breathing during sleep without associated ventilatory effort» [18]. CSA shows a specific breathing pattern called Cheyne-Stokes respiration and is identified as an independent risk factor contributing to the worsening of CHF and reducing survival of CHF patients [3].

1.2.3. Sleep Apnea - A Co-morbidity of CHF

«Obstructive sleep apnea (OSA) is considered a cause of CHF, whereas central sleep apnea (CSA) is considered a response to heart failure, perhaps even compensatory» [20]. Both types can occur together. Table 1.1 provides an overview on different studies which link heart failure and sleep apnea. These studies used an AHI of about 15 events per hour as threshold for diagnosing sleep apnea, nevertheless a comparison between them should be treated with care based on the various criteria defining sleep apnea. Due to these different criteria in diagnosing, estimation of prevalence of SDB in CHF population remains difficult.

Table 1.1.: Heart failure population studies related to sleep apnea syndrome

Study population	CSA	OSA	Source
1117	31%	47%	European Heart Journal [21]
700	40%	36%	European Journal of Heart Failure [22]
108	31%	30%	Journal of Clinical Sleep Medicine [23]
100	37%	12%	International Journal of Cardiology [24]

Figure 3.9 shows the distribution of CSA and OSA among a heart failure study population published in the European Heart Journal [21].

During the study period, 1117 patients underwent in-hospital overnight cardiorespiratory polygraphy between January 2007 and December 2010. 525 patients had OSA (47%), 344 suffered from CSA (31%) and 248 patients showed no or minimal symptoms (22%). [21]

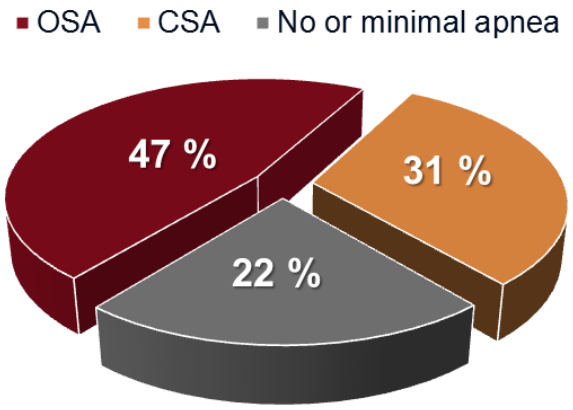

Figure 1.1.: Distribution of OSA and CSA among CHF population

1.3. Screening for SDB in CHF

The gold standard for diagnosing SDB in CHF is in-laboratory overnight polysomnography, performed by an attendant technician. The polysomnography includes continuous monitoring of multiple physiological parameters for at least one night. The relevant physiological parameters include respiration (respiratory effort, respiratory flow), snoring, oxygen saturation and the determination of sleep stages with electroencephalogram, electrooculogram and electromyogram [25]. The AHI is the most common parameter for determination of severity of CSA and OSA, respectively.

Since polysomnography is an expensive, time-consuming method with less capacity in regards to the large number of patients [26], alternative screening tools have been developed and evaluated to assess individuals' risk and perform a preselection. Questionnaires like the BQ and the STOP-

BANG are validated screening tools that concisely and reliably identify persons with a high risk for OSA. The BQ distinguishes between individuals who are at low risk or at high risk of having OSA by asking 9 questions, whereas the STOP-BANG classifies patients with low, intermediate and high risk of having OSA using 8 questions.

Patients with congestive heart failure commonly show symptoms from both sleep apnoea types occurring together, although one of these disordered breathing patterns may preponderate. Both questionnaires screen for frequent complaints reported by patients as snoring, excessive daytime sleepiness, fatigue, insomnia, shortness of breath during sleep, high blood pressure and body mass index (BMI). Further findings show symptoms which may occur due to CHF itself (example given: poor sleep quality, nocturia, frequent awakenings etc.). To consider these complaints the PSQI can be used to get additional information assessing patients sleep quality and disturbances. Table 1.2 provides information on reported symptoms and corresponding categories of the PSQI.

Table 1.2.: Additional scoring of sleep quality and disturbances using PSQI

Sleep apnea type	Patient reportet experiences	Category
CSA	Quality of sleep	Sleep quality
OSA	Morning headache	Sleep disturbances
CSA	Frequent awakenings	Sleep disturbances
CSA	Nocturia	Sleep disturbances/parameters
OSA	Sleep disruption	Sleep disturbances/parameters
-	Medication	Sleep medication

Due to findings from existing literature a risk profile was defined, including categories of both OSA screening questionnaires and of PSQI, as can

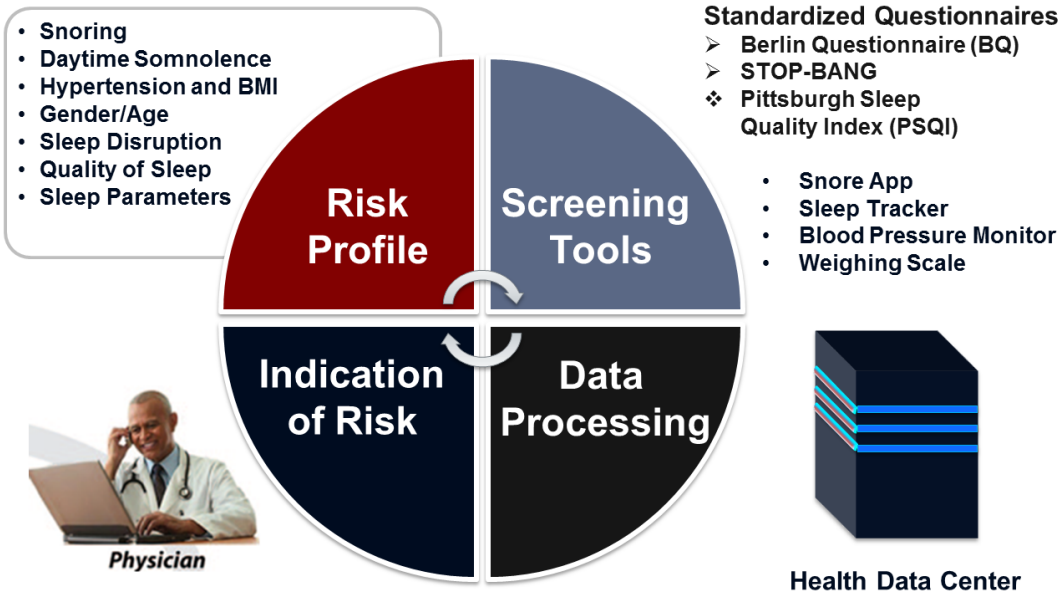

Figure 1.2.: Risk profile and corresponding screening tools. After screening, data could be transmitted to a health data center for further processing and visualization in order to provide it to a physician for continual indication of individuals' risk.

be seen in the upper left side of Figure 1.2. The upper right side shows the applied tools used for screening the defined risk profile, including sensors for quantification of suitable parameters. This continual risk assessing data could be transmitted to a health data center for further processing and visualization. Processed data could be provided to a physician in charge (bottom left) for continual indication of patients' risk. Further elaborations concerning therapy forms would go beyond the scope of this thesis and therefore a reference is made to the corresponding literature [27].

1.4. Master Thesis' Aim

Using standardized questionnaires by applying a specific *Time Schedule* to each question combined with mHealth represents a new approach to continually assess individuals' health state. Therefore, the objective of the present work includes three main tasks:

1 Development of a risk assessment concept to continually score sleep apnea in congestive heart failure patients at home using mHealth applications and standardized questionnaires.

2 Prototype development that implements this risk assessment concept by applying a mHealth-based telemonitoring platform solution provided by the AIT.

3 Conduction of a feasibility study of the prototype in 10 healthy volunteers

2. Methods

This chapter introduces a continual risk assessment method based on standardized questionnaires using mHealth, called the *Rolling Score Concept*. Processing of standardized questionnaires was performed with a text-processing pipeline of the open source analytic platform KNIME. A feasibility study was designed for a group of ten healthy subjects. Implementation of the concept was performed by means of a telehealth system.

2.1. The *Rolling Score Concept*

The inherent structure of standardized questionnaires can be divided into three levels, whereas each level is characterized by a distinct corresponding scoring. These three different levels are illustrated in Figure 2.1, showing Level I - Questionnaire, Level II Category and Level III Item, respectively. If some questionnaires do not allow a separation between Level I and II, each item was set as a category C_i. In this context, an item is referred to a question including response possibilities. Each item I_i has a defined score interval. Prescribed rule-sets 1 and 2 specify the transition between the three score levels.

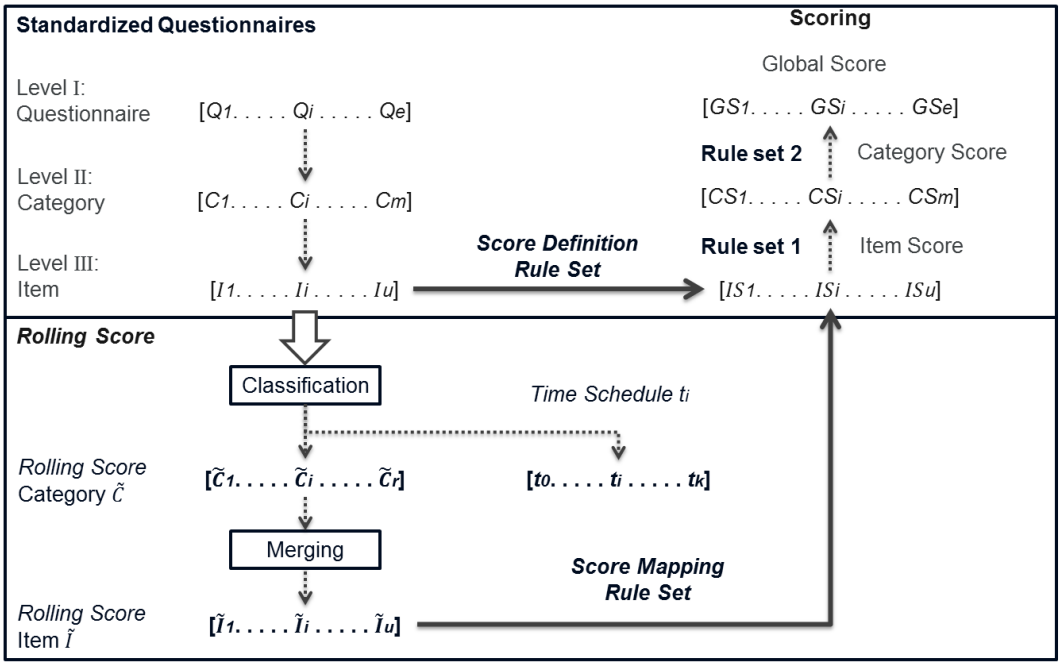

Figure 2.1.: The *Rolling Score Concept*: Scoring, classification, merging and mapping of standardized questionnaires

The *Rolling Score (RS) Concept* increased the degree of freedom of standardized questionnaires Q_i by adding a temporal dependency to the Global Score GS_i. Classification and merging of I_i was performed in regards to the semantic and temporal context in order to assign each I_i to a single and unique *RS* category $\tilde{C}_i$ and a specific *Time Schedule* t_i. To avoid the occurrence of semantically-identical items, a merging of items inside the same *RS* category was possible resulting in *RS* items $\tilde{I}_i$. An extracted *Score Mapping Rule Set* recalculated the respective Item Score IS_i.

All items of a standardized questionnaire had to be answered at the beginning (t_0) to generate an initial reference point, called *Initial Score*. Sub-

sequently, all categories were queried in accordance with the *Time Schedule*. After response, the assignment of item $\tilde{I}_i$ to the original IS_i was performed using the *Score Mapping Rule Set*, recalculating Category Score CS_i and Global Score GS_i with rule set 1 and 2, respectively. This led to a continual adaptation of the GS_i over time (Figure 2.2), thus it is named the *Rolling Score Concept*.

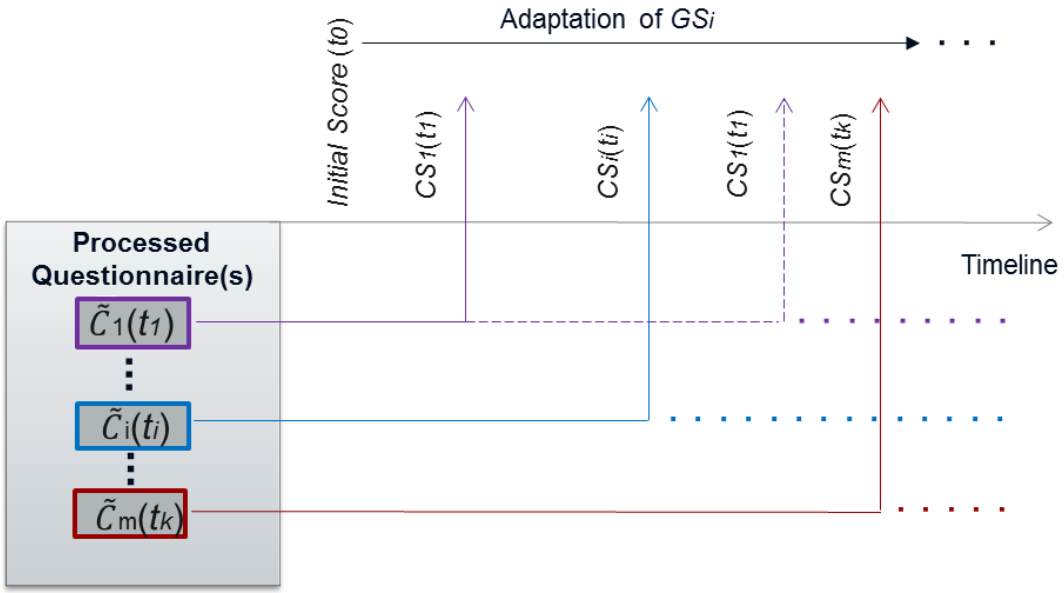

Figure 2.2.: Updating of the Global Score GS_i

The standardized questionnaire was asked again at the end of the feasibility study, generating an *End Score* in order to recognize deviations between the *Rolling Score* and the standardized score. A measure Δ_r (in percent) was defined to identify the deviation of the *GSi* and the respective *End Score* (Formula 2.1), where n was the total number of observations and *mSR* corresponded to the *maximum Score Range*.

$$\Delta_r = \frac{\frac{1}{n}\sum_{k=1}^{n}|GS_k - EndScore_k|}{mSR} * 100 \tag{2.1}$$

To compare deviations between the single questionnaires and the joined one, the relative measure δ_r (Formula 2.3, in percent) was defined. The variable u corresponded to the number of weeks. The variable δ_w represented the absolute average deviation per subject, whereas GS_v and GS_v^* corresponded to the last value of each week.

$$\delta_w = \frac{1}{u}\sum_{v=1}^{u}|GS_v - GS_v^*| \tag{2.2}$$

$$\delta_r = \frac{\frac{1}{n}\sum_{k=1}^{n}\delta_w}{mSR} * 100 \tag{2.3}$$

A compliance of the *RS* categories was defined as the ratio of the number of sent *RS* categories divided by the amount of received ones. Subjects with less than 75% of overall compliance were excluded from further data analysis regarding δ_r. This exclusion method was applied to the sub-analysis of δ_r only, as for a comparison between the single and joined questionnaires the total number of received *RS* categories was relevant.

2.1.1. Uncertainty of the *Rolling Score*

In the case of a missing answer to a scheduled time, an estimation for the resulting uncertainty was calculated. The uncertainty ϵ of GS_{BQ} and GS_{PSQI} can be seen in formula 2.4, estimating the deviation for each week separately. $CS_{i,max}$ was the maximal Category Score and p corresponded to the total

number of missing answers. The measure ϵ was defined in the range of the minimum to the maximum of the scoring system.

$$\epsilon = \begin{cases} p * (\pm CS_{i,max}), & \text{if } p \geq 1 \\ 0, & \text{if } p = 0 \end{cases} \tag{2.4}$$

In addition, a relative uncertainty ϵ_{rel} was defined (Formula 2.5).

$$\epsilon_{rel} = \frac{\epsilon}{mSR} \tag{2.5}$$

Due to the multiple item-dependency of the designed STOP-BANG scoring system, the uncertainty was calculated on the item level. To determine this uncertainty ϵ_{STOP}, the deviation of the IS_i was used (Formula 2.6). Calculation of the relative uncertainty $\epsilon_{STOP,rel}$ can be seen in Formula 2.7.

$$\epsilon_{STOP} = \begin{cases} m * (\pm IS_{i,max}), & \text{if m} \geq 1 \\ 0, & \text{if m = o} \end{cases} \tag{2.6}$$

$$\epsilon_{rel,STOP} = \frac{\epsilon_{STOP}}{\text{Number of Items}} \tag{2.7}$$

Exclusion Criteria Exclusion criteria for data analysis and risk screening were defined based on the risk classes of the scoring systems. Since two risk classes have been distinguished by the BQ, the exclusion criteria ξ_{BQ} were defined according to formula 2.8 ({} = set of numbers, [] = closed interval):

$$\xi_{BQ} = \begin{cases} GS_{BQ} = \{0, 3\} \wedge \epsilon_{rel,BQ} > 33.3\% \\ GS_{BQ} = [1, 2] \wedge \epsilon_{rel,BQ} > 0.0\% \end{cases} \tag{2.8}$$

As the PSQI and STOP-BANG distinguished 3 risk classes, exclusion criteria ξ_{PSQI} and $\xi_{STOP-BANG}$ were defined according to formula 2.9 and 2.10, respectively.

$$\xi_{PSQI} = \begin{cases} GS_{PSQI} = [0,2] \wedge \epsilon_{rel,PSQI} > 14.3\% \\ GS_{PSQI} = [3,13] \wedge \epsilon_{rel,PSQI} > 0.0\% \\ GS_{PSQI} = [14,19] \wedge \epsilon_{rel,PSQI} > 28.6\% \\ GS_{PSQI} = [20,21] \wedge \epsilon_{rel,PSQI} > 42.9\% \end{cases} \tag{2.9}$$

$$\xi_{STOP-BANG} = \begin{cases} \sum_{i=1}^{8} IS_i = \{0,7\} \wedge \epsilon_{rel,STOP} > 25.0\% \\ \sum_{i=1}^{8} IS_i = 1 \wedge \epsilon_{rel,STOP} > 12.5\% \\ \sum_{i=1}^{8} IS_i = [2,5] \wedge \epsilon_{rel,STOP} > 0.0\% \\ \sum_{i=1}^{8} IS_i = 8 \wedge \epsilon_{rel,STOP} > 37.5\% \end{cases} \tag{2.10}$$

If items contained BMI, neck circumference or gender and were answered with *Yes*, an $\epsilon_{rel,STOP}$ higher than 12.5% was set as exclusion threshold.

2.2. Classification and Merging

2.2.1. Characteristics of a Standardized Questionnaire

Standardized questionnaires have general characteristics [28] which were considered through all processing steps. These general characteristics are:

- A defined wording and order of items
- A defined response format of items

- Exact definition of items

2.2.2. Extraction of *Score Mapping Rule Set*

The text-processing tool of KNIME was used to perform an identification of items in regards to equal semantics. Since processing of standardized questionnaires is a critical task due to a loss of validation, the general characteristics were considered in the processing. A *Score Mapping Rule Set* performed a classification, consisting of a *Content-related Context Rule*, regarding wording and order, definition and response format of items, and a *Temporal Context Rule*.

A pipeline was set up to extract the *Content-related Context Rule* and ensure repeated outcome of questionnaire processing, including two main parts, a **keyword extraction** and an **identification of items**. For **keyword extraction**, pre-categorized questionnaires were used in order to ensure an independent identification of items. After keywords were assigned to a class, part two performed the identification of items of all applied questionnaires (Figure 2.3).

The first part loaded pre-categorized questionnaires by a pdf-parser. Parsed questionnaires were enriched using a part of speech (POS) tagging to assign each term to a specific tag. During preprocessing, all items were filtered for adverbs, adjectives and nouns. Additionally, stop words, special characters (punctuations, comma ...), numbers and characters with less than three words were filtered. After that, all words were converted to lower case to ensure unique assignment to a *RS* category.

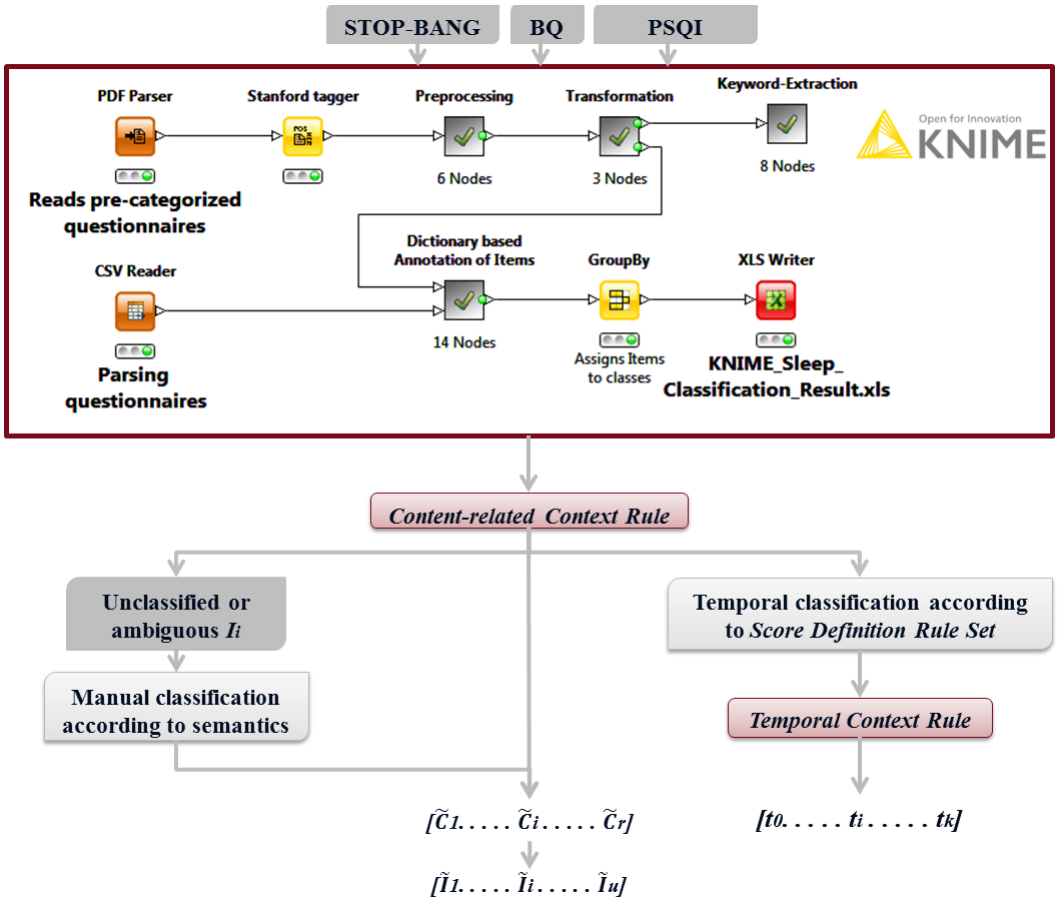

Figure 2.3.: Extraction of *Score Mapping Rule Set*

After preprocessing, a *bag of words* (BoW) was created, where each term showed a POS tag (noun, adverb, adjective). Tagged terms were grouped according to POS tag to extract keywords and subsequently, manual assignment of the keywords to their original category was done. Each category was assigned to a unique class-ID.

For **identification of items**, all keywords were used to built a dictionary for entity recognition. Parsed questionnaires were transformed to a doc-

ument format and then applied to the dictionary tagger. In the case of a matching keyword, the dictionary tagger annotated items through a specific assignment of a tag value and type. The annotated items were transformed, filtered and assigned to a unique class-ID.

As some items may have been classified in two or more *RS* categories or remained unclassified, manual classification according to semantics was performed. After extraction of a *Content-related Context Rule*, all items were assigned to a unique and coherent *RS* category.

Conduction of a temporal classification by applying the *Score Definition Rule Set* extracted the *Temporal Context Rule* in order to determine the *Time Schedule* t_i for each *RS* category.

Merging of items within the same *RS* category was possible, as *RS* items were already grouped regarding semantics and time. Two merging possibilities were applied: One method used a partial or complete replacement of one item by two or more analogous items with respect to semantics. A second method implied a disjunction to extend one item with the content of the replaced one. In the case of a mismatching response format between merged items, the largest score range was set as response format. Consequently, items may contain information about two or more original items. To regain this information, the *Score Mapping Rule Set* mapped the respective IS_i to the corresponding Ii.

2.3. Feasibility Study: *Rolling Score Concept* applied to Sleep Medicine

The concept of the *Rolling Score* has been applied to the questionnaires PSQI, STOP-BANG and BQ in the field of sleep medicine. The present concept was applied to each questionnaire separately as well as to all three combined to a joined questionnaire with merged items.

2.3.1. mHealth-based Telemonitoring Platform

A technical feasibility study was designed and conducted with the help of ten healthy volunteers over a period of one month. The business unit Assistive Healthcare Information Technology (AHIT) in the Department Digital Safety & Security (DSS) of AIT Austrian Institute of Technology provided a mHealth-based telemonitoring platform solution (KIOLA eHealth platform) for implementation of the *Rolling Score Concept*. The official field study name was *SleepMemory*.

The telemonitoring system consisted of three components (Figure 2.4):

1 **MobileMonitor:** Application on a smartphone to send and receive data. *RS* categories were sent to this app, and, after response, sent back to the system showing the user symbolically a successful data transfer. A check mark meant successful data transfer, whereas a flash symbol represented an error. In addition, vital signs like systolic and diastolic blood pressure, heart rate and weight could be transmitted.

2 **Web-Interface** for data access and compliance assessment. Protected by a password and accessible on the Internet.

3 **Data management system** for receipt and processing of data. Data export was possible for further analysis.

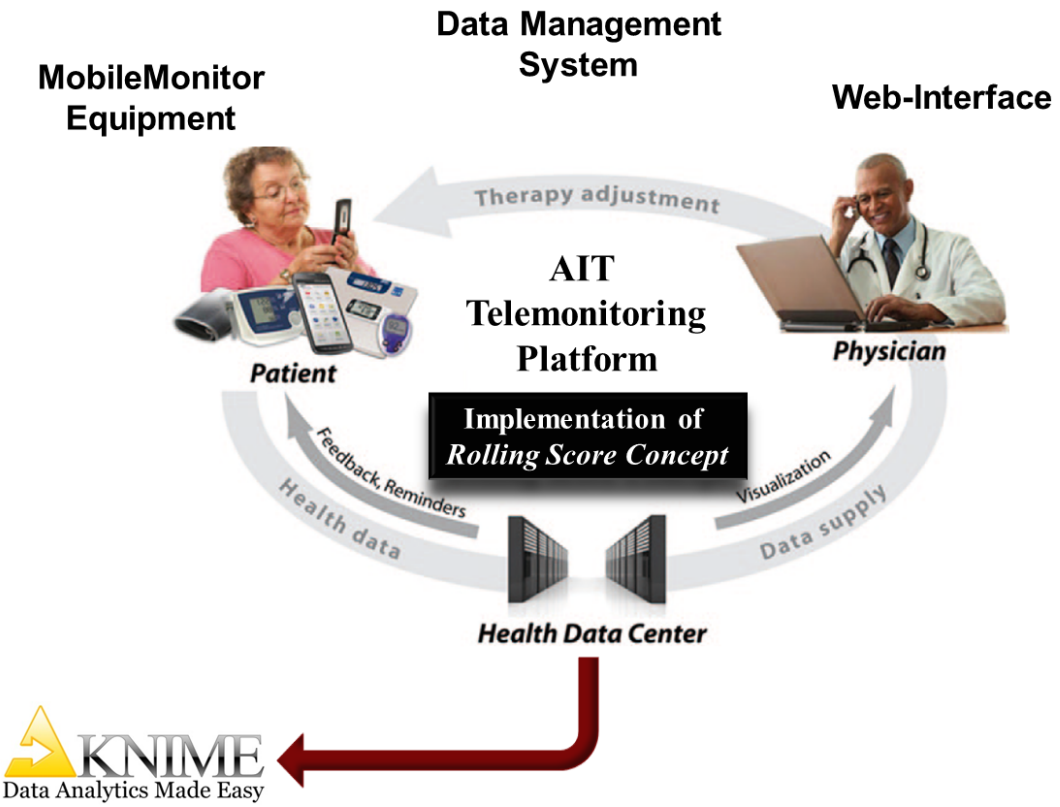

Figure 2.4.: The mHealth-based Telemonitoring Platform

Besides the MobileMonitor application, the equipment for the feasibility study consisted of a sleep tracker (*Withings® Pulse* O_X), a blood pressure monitor and a body weighing scale for collecting physiological data of the subjects at home. Both, the blood pressure monitor and the weighing scale

used the KIT concept of the AIT. The sleep tracker transmitted data via Bluetooth to a *Withings*® application on the smartphone, which synchronized several times a day with the Withings® server (internet access was required). An application programming interface (API), described in section 2.3.3, was implemented in the KIOLA eHealth platform for fetching sleep data each day. Additionally, a snore application was used as a stand-alone data collector (*SnoreClock*), generating a *snore-profile* on the internal storage of the smartphone. The snore app recorded acoustic signals (acoustic pressure profile) over night and stored it as an 3GP-file. After the extraction of the characteristic parameters of the acoustic pressure profile, these files had to be deleted by the user.

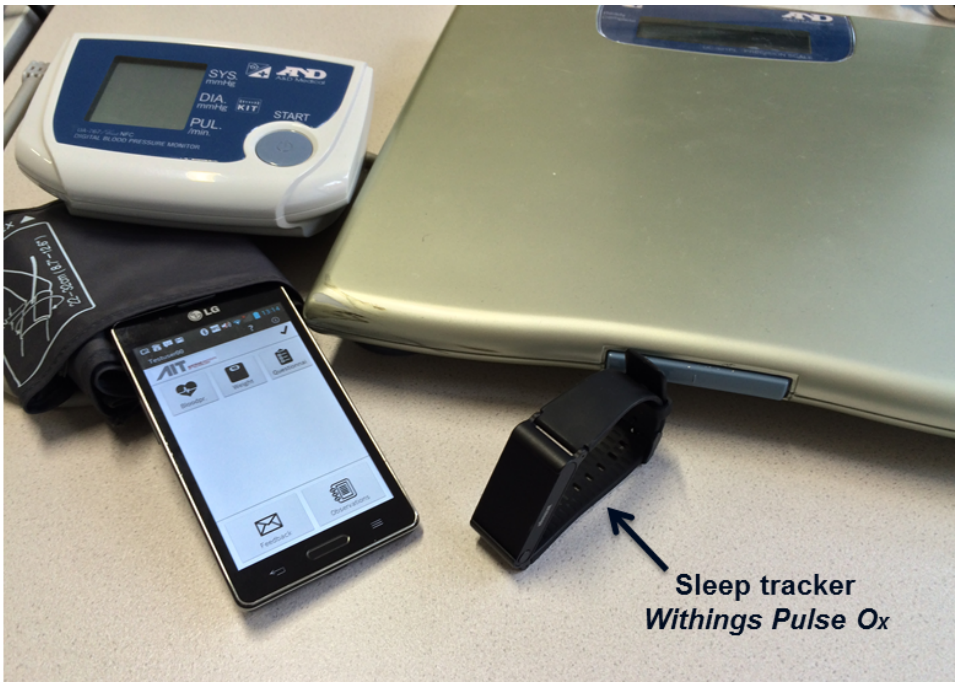

Figure 2.5.: Setting for feasibility study

To ensure data protection and to avoid reconstruction of data, the internal storage of the smartphone was deleted at the end of the field study by the coordinator. Figure 2.5 presents the equipment for the field study. The smartphone (LG Optimus L7 II, Android 4.1) shows the MobileMonitor application of AIT.

For a period of one month, subjects were instructed to answer all questions, to use the sleep tracker and snore app during their sleep and to measure blood pressure and weight in the morning. All subjects had to sign written informed consent due to data collection (see Appendix A). In addition, each subject received a sheet, containing information on the workflow regarding the use of the sensors (see Appendix A). Data has been transmitted to the telehealth platform for analysis and compliance check. The compliance for monitoring of snoring and sleep parameters was defined as the ratio between the number of conducted measurements and the total number of study days. Regarding the compliance for measurements of BMI and blood pressure, subjects were instructed to transmit one value per week. To be included in the BMI and blood pressure analysis, a total compliance equal or more than 75% was necessary.

2.3.2. Implementation of the *Rolling Score Concept*

The AIT provided a development server for implementation of the *Rolling Score Concept*. The development server was built in Django, a *Python Web Framework* for rapid development of web applications. In order to implement the concept and the sleep tracker API, a directory structure consisting of 5

python files was created:

- Pyxtures: Declaration of **Profiles**
- Cron: Implementation of *Time Schedule* logic
- Admin: Registration of subjects
- Models: Fetching start date and end date of registered subjects during study period
- Data_providers: *Withings*® API to fetch sleep data

Declaration of Profiles

The KIOLA eHealth platform used an object-orientated programming defining complex data types which corresponded to **Profiles**. The *RS* categories were implemented according to a 'tree structure' (Figure 2.6). Each *RS* category was attached to a **Root**, composing of a configurable *Title Content* and *Representation*, a *Date and Time* information and related *RS* items, attached in the form of 'branches' to the *RS* categories. Two settings of category representation were available, a *Singlepage* and a *Multipage* presentation. Each *RS* item was composed of a configurable *Question Content* and *Representation* and related *Responses*. *Radio-Buttons* and *Text-Fields* were used as response format of the items. The *Precondition*-option enabled to display an *RS* item depending on the response of a previous *RS* item. This option was only available by *Multipage*-representation of *RS* categories. According to the tree structure, each single response was handled as a 'branch' with configurable *Response Content*. An english and a german version of the applied

questionnaires was implemented.

The generation of an *Initial Score* and an *End Score* was performed by creating one **Root** for each applied questionnaire, attaching each item in the form of a *Multipage*-representation for clearly displaying.

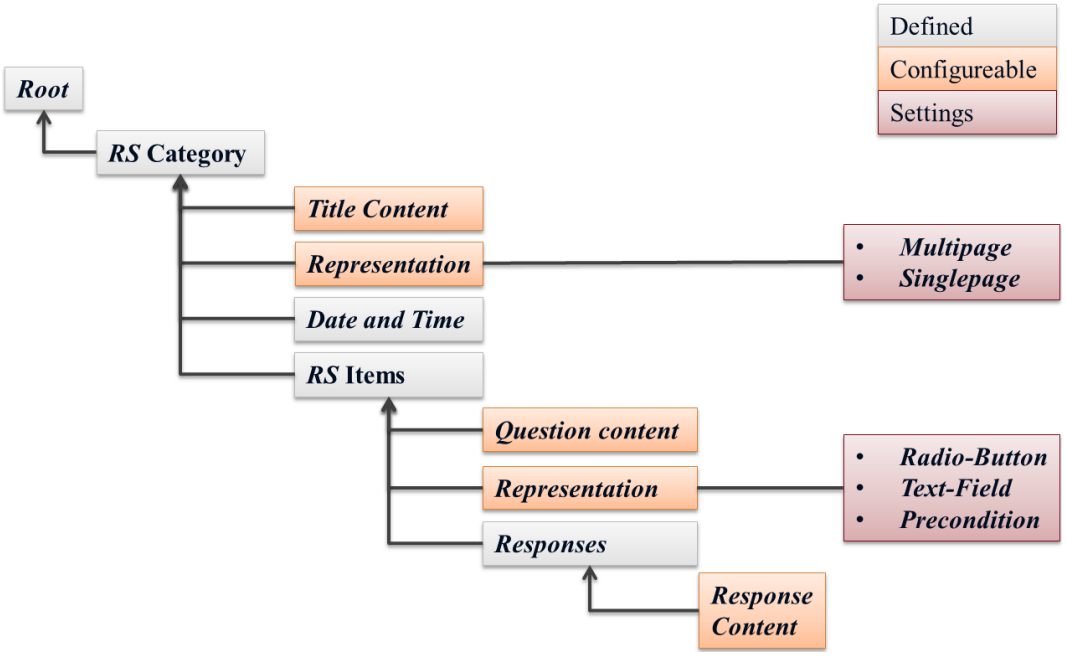

Figure 2.6.: Tree structure of *RS* categories

Setting up the *Time Schedule* using Django-cron

Specific cron classes [29] reflected the *Time Schedule* of the concept, sending *RS* categories and entire questionnaires according to a defined logic. The management command *python manage.py runcrons* was called from a created crontab and executed the cron logic according to a configurable value (for example: Five corresponded to an execution every five minutes). For each

cron class a parameter was set, defining when the cron class should run. This parameter could be a fixed value (corresponds to minutes), a time stamp (HH:MM) or a combination of both. In addition, a *FailedRunsNotificationCronJob* was integrated in order to check if there were unsuccessful cron jobs. In the case of ten unsuccessful events, an email will be sent to the coordinator.

Implementation of the *Time Schedule* was performed by four cron classes following a clear arrangement: *StartNotification*, *EndNotification*, *MonthlyQuestionnaireNotification* and *WeeklyQuestionnaireNotification*. Figure 2.7 represents the logic for the weekly and monthly notifications. The figure is only a schematic reflection of the logic and does not correspond 1:1 to the structure of the programme. The following steps were applied to each subject separately: At the beginning the existence of the registration date was checked to filter not completely registered subjects. In the *MonthlyQuestionnaireNotification* class, the current date was compared to the end date. The variable *time_diff* was computed, corresponding to the difference of the current date and the registration date. The use of the modulo operator ensured a monthly notification of the *RS* categories. The *WeeklyQuestionnaireNotification* class checked if the current date was within the interval of the start date (registration date plus one day) and the end date. The variable *week_day* was assigned a value from zero to six, whereas zero was Sunday and six Saturday, respectively.

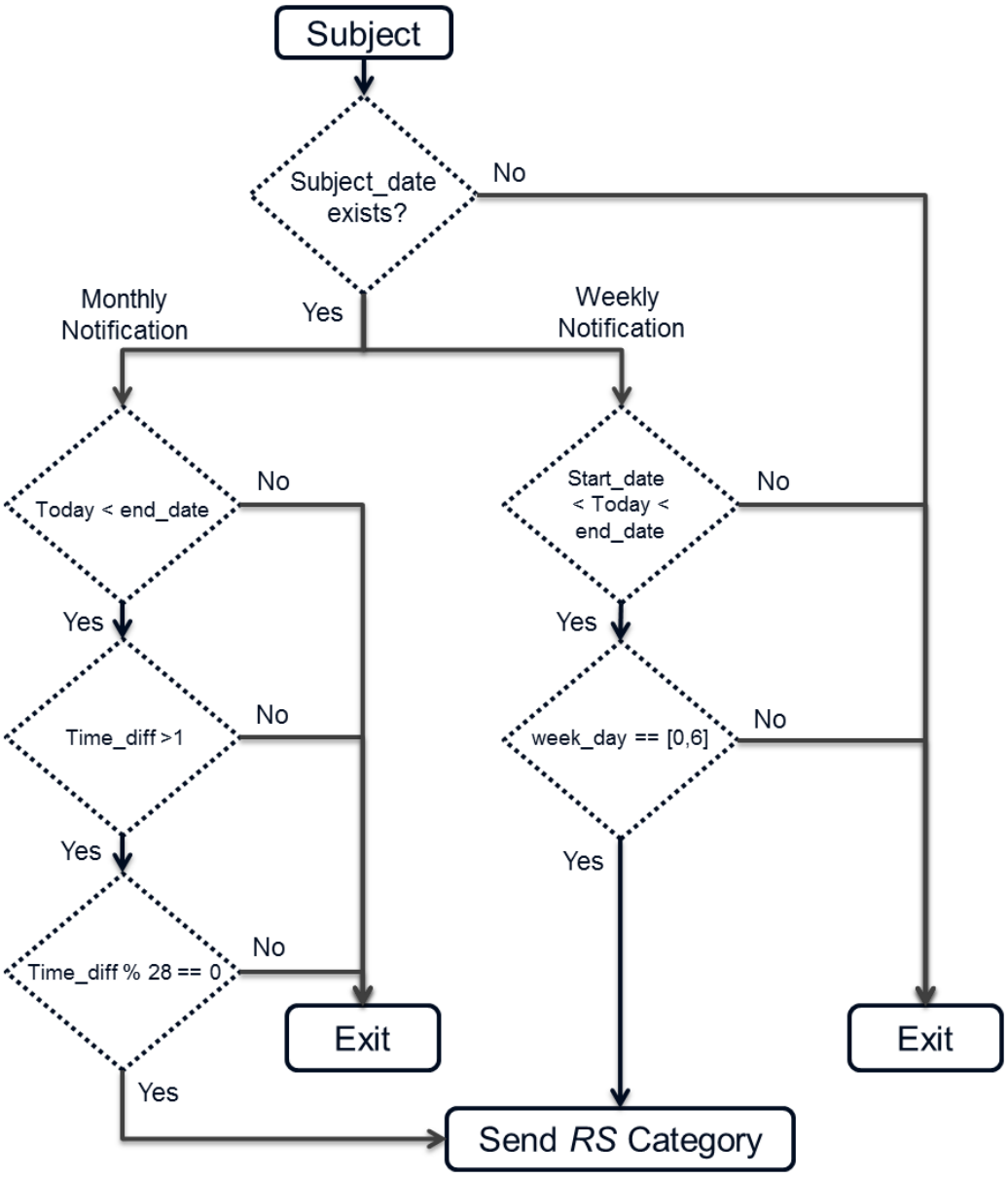

Figure 2.7.: Flowchart of *Time Schedule*

2.3.3. Implementation of the Sleep Tracker API

Withings® provided an API to fetch collected and stored data [30]. To get access to sleep information, it was necessary to use the *Withings*® API, which required the implementation of a four-step authentication part:

1 **get a oAuth request token:** Token to access users' data
2 **End-user authorization:** Special *Uniform Resource Identifier* (URL) that redirected user to the *Withings*® web site in order to allow application access to users' data.
3 **Generate access token:** A secret pair for fetching data of user.
4 **Access user data**: In the course of this work, the *Sleep Summary* URL was implemented.

After authentication was implemented, it was possible to access the *Sleep Summary* API. Requesting the *Sleep Summary*, the *Withings*® server responded with the required data in JavaScript Object Notation (JSON) data format. In order to store and process the JSON-formatted data in the telemonitoring system, seven numeric **Profiles** were created and used for parsing user data. The following parameters were fetched and stored in the system: *wakeupduration*, *lightsleepduration*, *deepsleepduration*, *durationtosleep*, *durationtowakeup* and *wakeupcount*. Except *wakeupcount*, all parameters were used to calculate sleep parameters which had a related *RS* item.

3. Results

The classification outcome of the *Rolling Score Concept* is illustrated separately for each questionnaire as well as for the combined one, showing new categories $\tilde{C}_i$, merged items $\tilde{I}_i$ and the *Time Schedule* t_i, respectively. The segmentation of a questionnaire through the application of a specific *Time Schedule* showed promising values ($\Delta_r < 8\%$). In addition, the deviation between the joined GS_i and the single questionnaires caused by the merging of items, showed little influence ($\delta_r < 6\%$). The *Rolling Score* as well as a possible uncertainty is presented with absolute and relative values and applied exclusion criteria. Mapping of processed items back to the corresponding item score by the *Score Mapping Rule Set* is shown by an example. Finally, analysis of the quantified items is presented.

3.1. The *Rolling Score*

The pipeline shown in Figure 2.3 was applied separately to BQ, STOP-BANG and PSQI, resulting in respective *RS* categories $\tilde{C}_i$, *RS* items $\tilde{I}_i$ and the *Time Schedule* t_i. Table 3.1 shows the outcome of the classified BQ. The predefined category *Blood Pressure* was replaced by the *RS* category *Monthly*

Quantifiable. The number of items corresponded to the number of *RS* items, as no merging was performable.

Table 3.1.: All categories C_i, $\tilde{C}_i$ and corresponding *Time Schedule* t_i of BQ

Category *C*	**Number of Items *I***	**Category $\tilde{C}$**	**Number of Items $\tilde{I}$**	***Time Schedule*** t_i
Snoring	5	Snoring	5	Mon.
Daytime Somnolence	3	Daytime Somnolence	3	Thu.
Blood Pressure	1	Monthly Quantifiable	1	Each 28^{th} after start
BMI	1	Monthly Quantifiable	1	Each 28^{th} after start

Applying the classification to PSQI, the outcome is illustrated in Table 3.2. No merging of items was possible as well.

Table 3.2.: All categories C_i, $\tilde{C}_i$ and corresponding *Time Schedule* t_i of PSQI
**One item of category *Sleep Duration* for GS_i calculation necessary

Category *C*	**Number of Items *I***	**Category $\tilde{C}$**	**Number of Items $\tilde{I}$**	***Time Schedule*** t_i
Sleep Disturbances	9	Sleep Disturbances	9	Tue.
Sleep Medication	1	Sleep Medication	1	Wed.
Daytime Somnolence	2	Daytime Somnolence	2	Thu.
Sleep Latency	2	Weekly Quantifiable	5	Fri.
Sleep Duration	1	Weekly Quantifiable	5	Fri.
Sleep Efficiency	2**	Weekly Quantifiable	5	Fri.
Sleep Quality	1	Sleep Quality	1	Each 28^{th} after start

As the STOP-BANG showed no predefined categories, application of the classification was not reasonable and therefore each item was handled as a separate *RS* category. Quantifiable items were manually assigned to the *RS* category *Monthly Quantifiable*. Since the items *Age* and *Gender* were only asked once at start, they have been grouped.

Table 3.3.: All categories C_i, $\tilde{C}_i$ and corresponding *Time Schedule* t_i of STOP-BANG

Category *C*	**Number of Items *I***	**Category $\tilde{C}$**	**Number of Items $\tilde{I}$**	***Time Schedule*** t_i
Snoring	1	Snoring	1	Mon.
Observed	1	Observed	1	Mon.
Daytime Somnolence	1	Daytime Somnolence	1	Thu.
Blood Pressure	1	Monthly Quantifiable	3	Each 28^{th} after start
BMI	1	Monthly Quantifiable	3	Each 28^{th} after start
Neck Size	1	Monthly Quantifiable	3	Each 28^{th} after start
Age/Gender	2	Age/Gender	2	At start

The application of the classification and merging methods to all three questionnaires resulted in *RS* categories $\tilde{C}_i$, *RS* items $\tilde{I}_i$ and the *Time Schedule* t_i (Table 3.4). The overall number of 13 categories was reduced to eight *RS* categories. In order to reduce the daily effort, the weekly *Time Schedule* had a distribution from Monday to Friday, including the *RS* categories *Daytime Somnolence*, *Snoring*, *Sleep Medication*, *Weekly Quantifiable* and *Sleep Disturbances*.

Table 3.4.: All categories C_i, $\tilde{C}_i$ and corresponding *Time Schedule* t_i
*Order: STOP-BANG/BQ/PSQI ** One item of category *Sleep Duration* for GS_i calculation necessary

Category *C*	**Number of Items *I***	**Category $\tilde{C}$ (Number of Items $\tilde{I}$)**	**Number of Items $\tilde{I}$**	***Time Schedule*** t_i
Snoring	1/5*	Snoring (8)	4	Mon.
Observed	1	Snoring (8)	4	Mon.
Sleep Disturbances	9	Sleep Disturbances (8)	8	Tue.
Sleep Medication	1	Sleep Medication (1)	1	Wed.
Daytime Somnolence	1/3/2*	Daytime Somnolence (6)	4	Thu.
Sleep Latency	2	Weekly Quantifiable (5)	5	Fri.
Sleep Duration	1	Weekly Quantifiable (5)	5	Fri.
Sleep Efficiency	2**	Weekly Quantifiable (5)	5	Fri.
Blood Pressure	2	Monthly Quantifiable (4)	3	Each 28^{th} after start
BMI	1	Monthly Quantifiable (4)	3	Each 28^{th} after start
Neck Size	1	Monthly Quantifiable (4)	3	Each 28^{th} after start
Sleep Quality	1	Sleep Quality (1)	1	Each 28^{th} after start
Age/Gender	2	Age/Gender (2)	2	At start

After the start of the field study, the categories *Sleep Quality*, *Blood Pressure*, *BMI* and *Neck Size*, summarized in the *RS* category *Monthly Quantifiable*, were asked every 28^{th} day, as defined by the *Score Definition*. The *RS* category *Age/Gender* was only asked once at the beginning.
Each questionnaire was asked separately (single *RS*) and, in addition, all three questionnaires were asked as a combined one (joined *RS*) with equal *Time Schedule* t_i. The *Initial Score* was a reference point for updating the GS_i, corresponding to the Global Score of a standardized questionnaire. The maximal score interval of $GS_{STOP-BANG}$, GS_{BQ} and GS_{PSQI} ranged from 0 to 2, 0 to 3 and 0 to 21, respectively. As the STOP-BANG questionnaire showed no Global Score in the form of a number, the following risk scale was defined: low risk $\widehat{=}$ 0, intermediate risk $\widehat{=}$ 1 and high risk $\widehat{=}$ 2. The time period was set at four weeks because the questionnaires did not distinguish between assessing risk within four weeks or one month [8].

At the end of the field study (29^{th} day), the subjects were instructed to complete the entire standardized questionnaires again in order to generate an *End Score*. This *End Score* was used to find deviations between the standardized Global Scores and the *RS* of both, the joined and single questionnaires' GS_i. Table 3.5 provides information on arithmetic mean, standard deviation and Δ_r of each GS_i and corresponding *End Score* over all subjects. For BQ, all subjects were included in the calculation of GS_i, GS_i^*, Δ_r and Δ_r^* based on exclusion criteria (Formula 2.8). For calculation of Δ_r/Δ_r^* and GS_i/GS_i^* of STOP-BANG, subject 09 was excluded (Formula 2.10). The GS_i, GS_i^*, Δ_r and Δ_r^* of PSQI was calculated, excluding subject 04 and 09 (Formula 2.9).

Table 3.5.: Arithmetic mean, standard deviation and Δ_r of single and joined GS_i and *End Score*, *joined questionnaires

Questionnaire	GS_i*	GS_i	*End Score*	Δ_r *	Δ_r
BQ	0.4 ± 0.5	0.4 ± 0.5	0.5 ± 0.5	3.3%	3.3%
STOP-BANG	0.2 ± 0.7	0.2 ± 0.7	0.2 ± 0.7	0.0%	0.0%
PSQI	4.6 ± 2.5	3.9 ± 2.5	4.6 ± 1.8	6.0%	7.1%

Figure 3.1 shows a *RS* of BQ at health level (a score of 1 corresponded to low risk) with a matching of the *End Score* and the *RS* of both, the joined and single questionnaire.

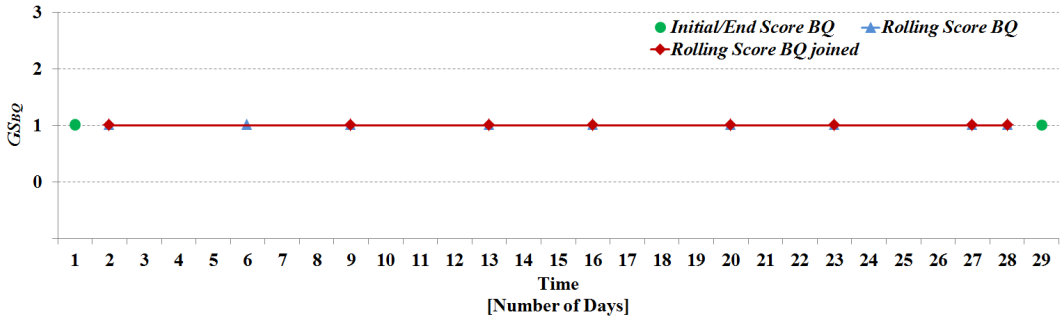

Figure 3.1.: The *Rolling Score* of joined and single BQ of Subject 06

Figure 3.2 illustrates a temporal variance (all GS_i changed), showing a mismatching of the single and joined *RS* of STOP-BANG.

The *RS* of single and joined PSQI of subject 06 is illustrated in Figure 3.3, showing a mismatching of the GS_{PSQI} between the joined and the single questionnaire as well as a mismatching of the single and joined GS_{PSQI} and the *End Score*.

Considering all subjects, the GS_i were at low risk with a minimal temporal variance. Subject 09 and 06 had a temporal increase of the $GS_{STOP-BANG}$ at

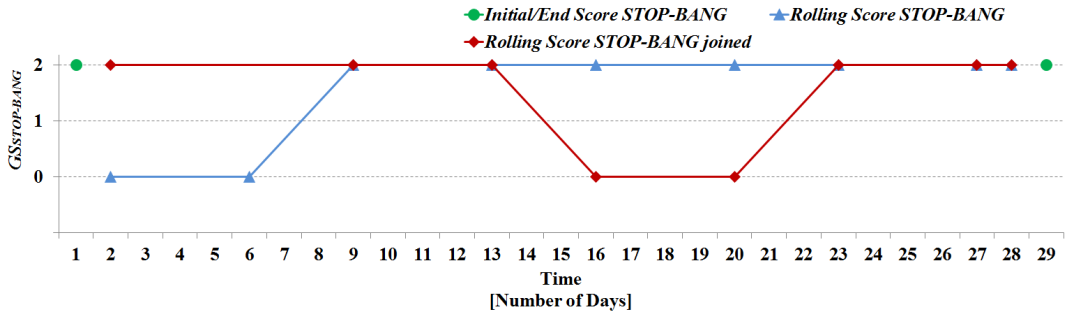

Figure 3.2.: The *Rolling Score* of joined and single STOP-BANG of Subject 06

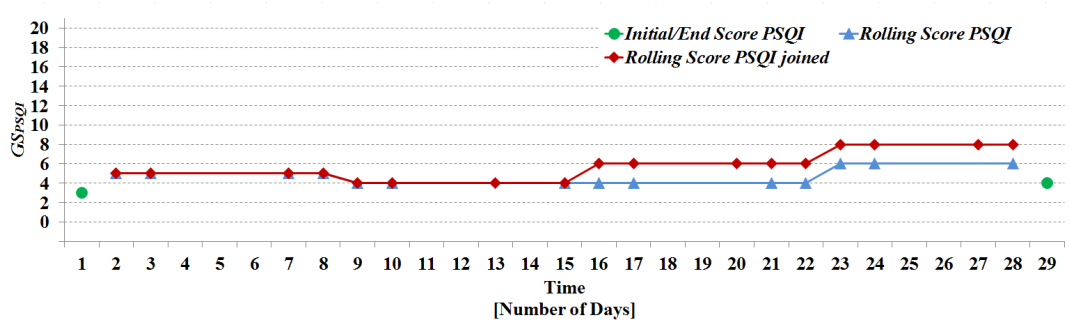

Figure 3.3.: The *Rolling Score* of joined and single PSQI of Subject 06

high risk level. According to PSQI, subject 01 was identified as a *bad sleeper* and subject 03, 04 and 06 showed a temporal increase in the scoring level of a *bad sleeper*.

A comparison of the joined and single GS_i was performed using the measure δ_r (Formula 2.3). As the registration date of subjects was shifted among them, subjects have started with different *RS* categories. Consequently, calculation of the daily deviation was not meaningful and a comparison of the last GS_i per week has been performed (Formula 2.2). As the analysis of the deviations between the single and joined questionnaire depended on the number of received *RS* categories, the compliance was used as exclusion

Table 3.6.: Arithmetic mean, standard deviation and δ_r of GS_i

Questionnaire	GS	δ_r
BQ	0.1 ± 0.3	2.8%
STOP-BANG	0.1 ± 0.3	5.5%
PSQI	0.3 ± 0.4	1.5%

criterion. Subject 04 was excluded for all GS_i and subject 05 for PSQI only. A comparison between the joined and single questionnaires indicate a minor impact of the merging of specific items, as can be seen in Table 3.6.

3.1.1. Uncertainty of the *Rolling Score*

A total of 45 *RS* categories were missing, causing an uncertainty of the GS_i. This uncertainty of the *Rolling Score* is defined by the maximal value of the CS_i (Formula 2.4). As can be seen in Figure 3.4, a missing update of the *RS* category *Snoring* led to an uncertainty in the range of 0 to 1 ($CS_{i,max} = \pm 1$) described as a band. This band decreased to zero after the respective CS_i was updated again. For BQ, ϵ is defined in the interval of $0 \leq \epsilon \leq 3$.

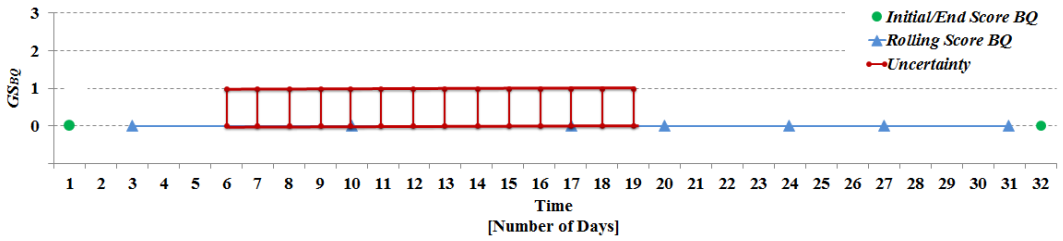

Figure 3.4.: Uncertainty of the GS_{BQ} of subject 04

Figure 3.5 illustrates the additively increasing propagation of the uncertainty if more than one *RS* category per week was missing (from day 21 to

23). This uncertainty of the *Rolling Score* remained until an update led to a decrease in the range of the respective $CS_{i,max}$. In the case of the PSQI, this value was in the range of ± 3. For PSQI, ϵ is defined in the interval of $0 \leq \epsilon \leq 21$.

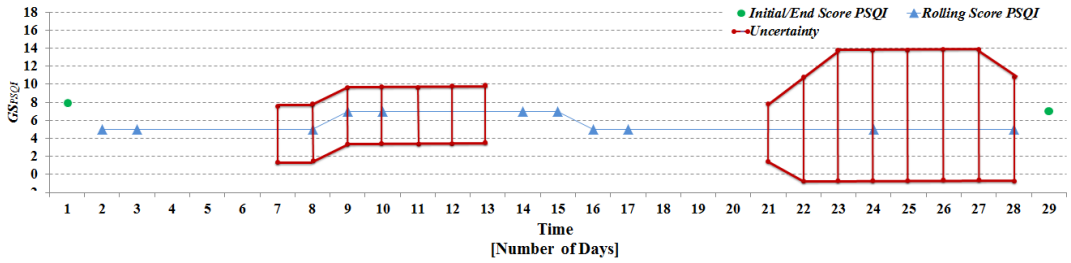

Figure 3.5.: Uncertainty of the GS_{PSQI} of subject 09

Depending on the number of questions answered with *Yes*, the uncertainty $\epsilon_{STOP-BANG}$ may extend to the entire scoring range (Figure 3.6) as defined in Formula 2.10. ϵ_{STOP} is defined in the interval of $0 \leq \epsilon \leq 8$.

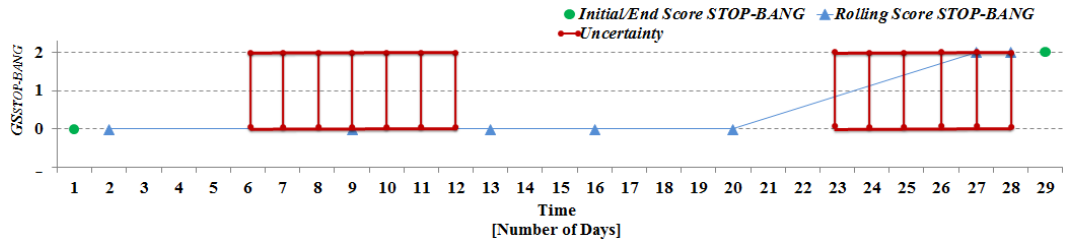

Figure 3.6.: Uncertainty of the $GS_{STOP-BANG}$ of subject 09

In addition to the absolute uncertainty of the *Rolling Score*, relative values (Formula 2.5 and 2.7) were calculated. Table 3.7 shows the *Initial Score*, the *End Score*, the *Rolling Score* and the relative uncertainty of each subject for BQ.

Table 3.7.: The *Rolling Score* and ϵ_{rel} of single and joined* BQ of all subjects

Subject	***Initial Score***	***Rolling Score* of BQ**				***End Score***
		Week 1	Week 2	Week 3	Week 4	
01	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
01*	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
02	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
02*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
03	1	2 ± 0.0%	1 ± 0.0%	1 ± 0.0%	0 ± 0.0%	1
03*	1	1 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	1
04	0	0 ± 33.3%	0 ± 33.3%	0 ± 0.0%	0 ± 0.0%	0
04*	0	0 ± 0.0%	0 ± 33.3%	0 ± 0.0%	0 ± 0.0%	0
05	0	0 ± 33.3%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
05*	0	0 ± 33.3%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
06	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
06*	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
07	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
07*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
08	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
08*	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
09	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
09*	1	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1 ± 0.0%	1
10	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
10*	0	0 ± 33.3%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0

Table 3.8 shows the *Initial Score*, the *End Score*, the *Rolling Score* and the relative uncertainty of each subject for STOP-BANG.

Table 3.8.: The *Rolling Score* and $\epsilon_{rel,STOP}$ of single and joined* STOP-BANG of all subjects

Subject	***Initial Score***	***Rolling Score* of STOP-BANG**				***End Score***
		Week 1	Week 2	Week 3	Week 4	
01	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
01*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
02	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
02*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
03	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
03*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
04	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
04*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
05	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
05*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
06	2	0 ± 0.0%	2 ± 0.0%	2 ± 0.0%	2 ± 0.0%	2
06*	2	2 ± 100.0%	2 ± 0.0%	0 ± 0.0%	2 ± 0.0%	2
07	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
07*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
08	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
08*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
09	0	0 ± 100.0%	0 ± 0.0%	0 ± 0.0%	2 ± 100.0%	2
09*	0	0 ± 100.0%	0 ± 100.0%	0 ± 0.0%	2 ± 0.0%	2
10	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0
10*	0	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0 ± 0.0%	0

Table 3.9 shows the *Initial Score*, the *End Score*, the *Rolling Score* and the relative uncertainty of each subject for PSQI.

Table 3.9.: The *Rolling Score* and ϵ_{rel} of single and joined* PSQI of all subjects

Subject	***Initial Score***	***Rolling Score* of PSQI**				***End Score***
		Week 1	Week 2	Week 3	Week 4	
01	6	$7 \pm 0.0\%$	$8 \pm 0.0\%$	$8 \pm 0.0\%$	$8 \pm 0.0\%$	7
01*	6	$8 \pm 0.0\%$	$8 \pm 0.0\%$	$8 \pm 0.0\%$	$8 \pm 0.0\%$	7
02	9	$4 \pm 0.0\%$	$4 \pm 0.0\%$	$4 \pm 0.0\%$	$4 \pm 0.0\%$	7
02*	9	$4 \pm 0.0\%$	$4 \pm 0.0\%$	$4 \pm 0.0\%$	$4 \pm 0.0\%$	7
03	5	$6 \pm 0.0\%$	$6 \pm 0.0\%$	$6 \pm 0.0\%$	$5 \pm 0.0\%$	5
03*	5	$6 \pm 0.0\%$	$6 \pm 0.0\%$	$6 \pm 0.0\%$	$5 \pm 0.0\%$	5
04	4	$5 \pm 0.0\%$	$4 \pm 42.9\%$	$5 \pm 14.3\%$	$3 \pm 42.9\%$	2
04*	4	$6 \pm 0.0\%$	$6 \pm 42.9\%$	$6 \pm 14.3\%$	$5 \pm 42.9\%$	2
05	4	-	$4 \pm 14.3\%$	$5 \pm 0.0\%$	$2 \pm 0.0\%$	4
05*	4	-	$4 \pm 0.0\%$	$5 \pm 0.0\%$	$4 \pm 0.0\%$	4
06	3	$5 \pm 0.0\%$	$4 \pm 0.0\%$	$4 \pm 0.0\%$	$6 \pm 0.0\%$	4
06*	3	$5 \pm 0.0\%$	$4 \pm 0.0\%$	$6 \pm 0.0\%$	$8 \pm 0.0\%$	4
07	6	$4 \pm 0.0\%$	$3 \pm 0.0\%$	$3 \pm 0.0\%$	$2 \pm 0.0\%$	2
07*	6	$4 \pm 0.0\%$	$4 \pm 0.0\%$	$4 \pm 0.0\%$	$2 \pm 0.0\%$	2
08	2	$1 \pm 0.0\%$	$2 \pm 0.0\%$	$2 \pm 0.0\%$	$0 \pm 0.0\%$	2
08*	2	$1 \pm 0.0\%$	$2 \pm 0.0\%$	$2 \pm 0.0\%$	$1 \pm 0.0\%$	2
09	8	$5 \pm 14.3\%$	$7 \pm 0.0\%$	$5 \pm 28.6\%$	$5 \pm 14.3\%$	7
09*	8	$5 \pm 14.3\%$	$7 \pm 0.0\%$	$5 \pm 28.6\%$	$5 \pm 14.3\%$	7
10	5	$4 \pm 0.0\%$	$3 \pm 28.6\%$	$4 \pm 0.0\%$	$4 \pm 0.0\%$	5
10*	5	$4 \pm 14.3\%$	$4 \pm 28.6\%$	$4 \pm 0.0\%$	$5 \pm 0.0\%$	5

3.2. Classification and Merging

The classification pipeline (Figure 2.3) was applied to a total of 35 items without considering the text of the prescribed response possibilities of the three questionnaires.

3.2.1. Keyword-Extraction

The steps of POS, preprocessing and transformation for keyword extraction are illustrated exemplarily with an item of PSQI:

5.During the past month, how often have you had trouble sleeping because you ... E. Cough or snore loudly?

The Part-of-Speech-Tagging assigned each word to a specific POS tag, whereas the abbreviations in the square brackets corresponded to the respective part of speech (An exact definition of the abbreviations is available in [31]):

5	[CD]	how	[WRB]	because	[IN]
.	[SYM]	often	[RB]	Cough	[VBP]
During	[IN]	have	[VBP]	or	[CC]
the	[DT]	you	[PRP]	snore	[VBP]
past	[JJ]	had	[VBD]	loudly	[RB]
month	[NN]	trouble	[NN]	PSQI	[NNP]
,	[SYM]	sleeping	[VBG]	Questionnaire	[NNP]

Afterwards the tagged words were filtered for adverbs, adjectives and nouns and converted into small letters due to easier further processing:

past	[JJ]	sleeping	[VBG]	psqi	[NNP]
month	[NN]	cough	[VBP]	questionnaire	[NNP]
trouble	[NN]	snore	[VBP]		

To support keyword extraction, the frequency of each word was computed. Only uniquely assignable words have been defined as a keyword for a *RS* category. For example, the words *sleep*, *sleepy* or *sleeping* were not chosen as keywords, as they played a key role in sleep-related questionnaires and, consequently, would have led to ambiguous classified items.

3.2.2. Identification of Items

All 9 items of BQ were classified to 3 *RS* categories. For PSQI, 7 items remained unclassified. Five of the involved items could be quantified and were assigned to the respective *RS* category *Weekly Quantifiable*. The remaining two were assigned manually to their origin category. **Identification of items** of all three combined questionnaires assigned 24 items to a unique and coherent *RS* category, whereas 10 items remained unclassified and one item was classified in two *RS* categories. The respective un- and ambiguous classified items were assigned manually to a unique *RS* category according to semantics. In Appendix B.1, further results of the identification process can be seen.

3.2.3. *Score Mapping Rule Set*

The merging method summarized a total of 35 items to 28 *RS* items (Appendix B.2). Table 3.10 shows two items before and after they were merged

through a disjunction. The extracted keyword of these items was *breathing*, assigning them into the same *RS* category.

Table 3.10.: Merging of two items through a disjunction

BQ I_5	STOP-BANG I_3	$\tilde{I}_4$
Has anyone noticed that you quit breathing during your sleep?	Has anyone Observed you Stop Breathing or Choking/Gasping during your sleep?	Has anyone noticed that you quit breathing or suffer from breathing problems (Choking/Gasping) during your sleep?

Figure 3.7 shows three items from different questionnaires with respective IS_i before classification and merging was applied.

BQ *I7*	**BQ *IS7***	**STOP-BANG *I2***	**STOP-BANG *IS2***	**PSQI *I9***	**PSQI *IS9***
During your waking time, do you feel tired, fatigued or not up to par?		Tired? Do you feel Tired, Fatigued or Sleepy during the daytime[…]?		During the past month, how much of a problem has it been for you to keep up enough enthusiasm to get things done?	
o Nearly every day	1	o Yes	1	o No problem at all	0
o 3-4 times a week	1	o No	0	o Only a very slight problem	1
o 1-2 times a week	0			o Somewhat of a problem	2
o 1-2 times a month	0			o A very big problem	3
o Never or nearly never	0				

Figure 3.7.: Three items before classification and merging

To recalculate each IS_i, the *Score Mapping Rule Set* was used (Table 3.11). The *Score Definition Rule Set* determined the *Time Schedule*. For $\tilde{I}_3$, the dashed line in Table 3.11 labels exemplarily this cut-off value. The arrows in the column *Threshold* mark the applied variations of the threshold, varying from a hard, middle and soft value corresponding to the threshold levels 3, 2 and 1, respectively. During the mapping of the Item Scores, the threshold was

Table 3.11.: Merged $\tilde{I}_3$ and corresponding *Score Mapping Rule Set*

Category $\tilde{2}$ *Daytime Somnolence* $\tilde{I}_3$	***Score Mapping Rule Set***		
During your waking time, do you feel tired, fatigued or not up to par?	1:1 Mapping	Threshold	Arithemtic Mean
o Nearly every day	1	1	3
o 3-4 times a week	1	1 ↑	3
o 1-2 times a week	0	0 ↓	2
-			
o Never or nearly never	0	0	0

varied to find the best fit between the single questionnaire and the joined one. Only one subject showed a difference when varying the threshold (Figure 3.8). This difference can be seen using a threshold of level 3. For data analysis, the middle threshold was set, since it showed the best fit.

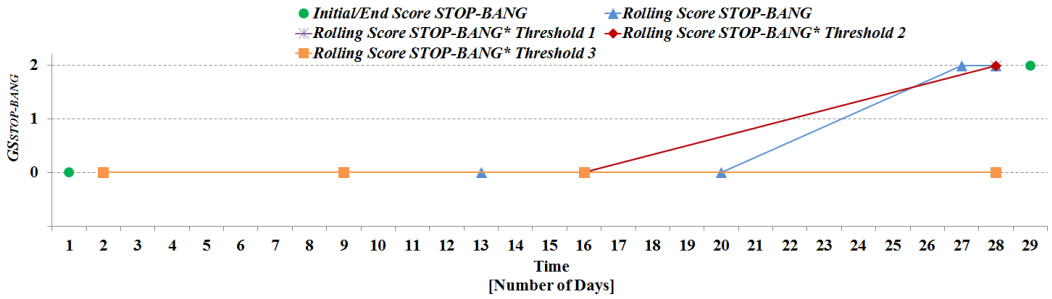

Figure 3.8.: Variations of threshold

Assessment and scoring of sleep quality and disturbances over a period of one month was performed using the PSQI. As some categories were asked weekly based on definitions of the *Time Schedule*, information on three weeks before was not taken into account. Therefore, the application of the *Score Mapping Rule Set* regained this information by considering the score of the last four weeks. The arithmetic mean of the IS_i at the present day t_i and the Item Scores of the past three weeks was used for a correct mapping.

3.3. Feasibility

Between December 2015 and January 2016 a feasibility study was conducted, applying the *Rolling Score Concept* to ten healthy volunteers. Participants were equipped with a smartphone and an app for questionnaire completion, a snore application, a sleep tracker, a blood pressure monitor and a weighing scale.

The mHealth application provided a separate tile for blood pressure and weight measurements and for completion of questions (Figure 3.9). It was possible to send the participant feedback in the form of a message. The check symbol on the top right section indicates if all data was successfully transmitted to the back-end. The appearance of a lightning instead of the check symbol pointed out that the server had blocked the transmission. The tile *Observations* provided information about successful and unsuccessful transfer of data.

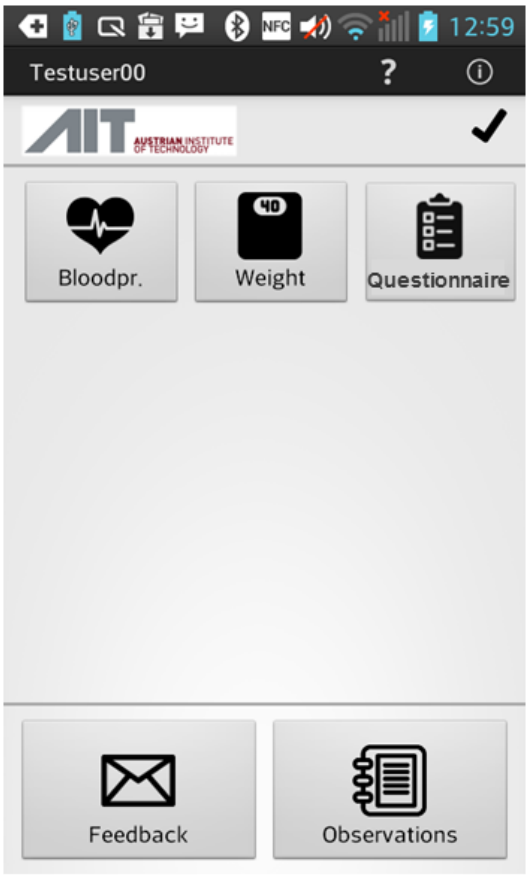

Figure 3.9.: Main screen of used mHealth application

The registration in the telehealth system was performed by a study coordinator assigning each subject a unique number to avoid identification among them. For data analysis, informed consent was obtained from each subject and archived electronically. The *RS* categories were sent at 02:00 am to the mobile application.

Figure 3.10 shows one *RS* item of the category *Daytime Somnolence*. Responses of items were implemented in the form of radio buttons and text fields. The top of the screen shows the length of the questionnaire, id est the number of *RS* items per *RS* category. The conduction of a feasibility study tested the prototype of the *Rolling Score Concept*. Therefore, the functionality of the workflow was an essential part of this work (interaction of user, mHealth application and back-end as well as a successful data transmission) rather than the layout of the questions.

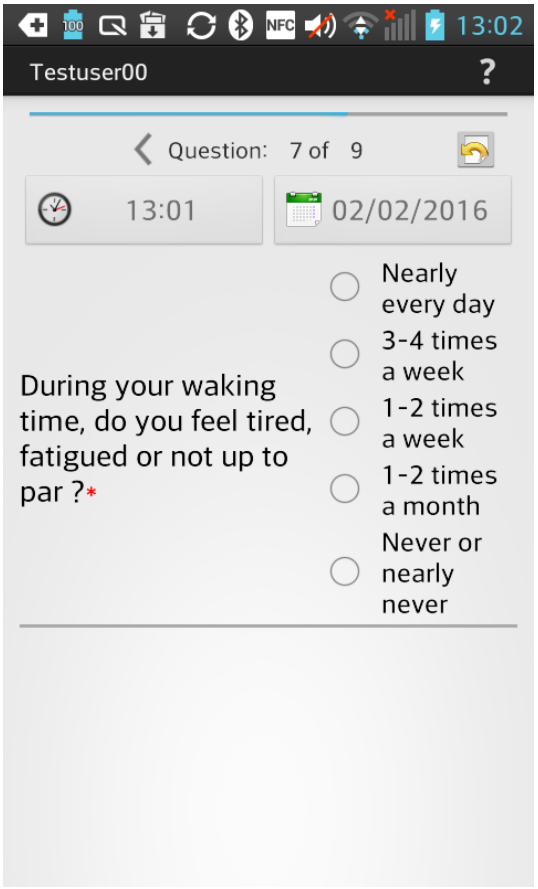

Figure 3.10.: *RS* item of *RS* category *Daytime Somnolence*

Demographic Data

Table 3.12 shows demographic data of the study population. The proportion between men and womean was 70% and 30%, respectively and the average age was 29,1. Additionally, the height was collected for calculation of BMI.

Table 3.12.: Demographic data of study population

Subject ID	Age	Gender	Height
01	27	male	1.88m
02	26	female	1.65m
03	26	male	1.86m
04	26	female	1.70m
05	23	male	1.85m
06	46	male	1.83m
07	26	female	1.66m
08	27	male	1.78m
09	31	male	1.81m
10	33	male	1.80m

3.3.1. Compliance

In the course of the feasibility study, 463 *RS* categories were sent to the front-end without any errors, and the back-end received 420 RS categories. Due to a lack of compliance, 43 *RS* categories were missing, resulting in an overall compliance of 90.7%. The overall compliance for each subject and questionnaire can be seen in Figure 3.11. The compliance was used as inclusion criterion for the sub-analysis of δ_r.

The long dashed line marks the threshold for data analysis. Further information on compliance is available in Appendix D.1. The occurrence of two technical errors did not disturb the workflow. Both errors had the same

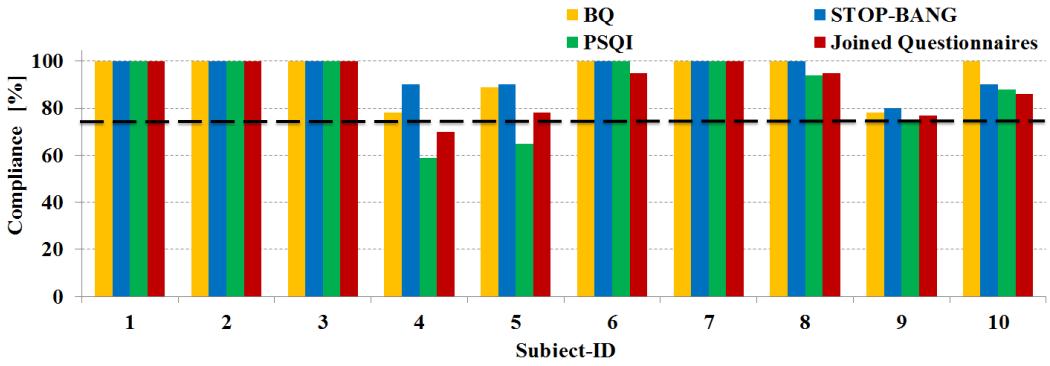

Figure 3.11.: Compliance per subject

source, as two subjects entered a space character which was interpreted as a missing value by the programme. The system did not accept missing values and therefore refused the synchronization process.

Table 3.13 shows the compliance of all subjects in regards to the monitoring of sleep efficieny, sleep latency and sleep duration (sleep parameters), snoring, body weight and blood pressure. Only four subjects transmitted at least one weight and systolic and diastolic blood pressure value per week and were included in BMI calculation. Regarding the sleep parameters, subject 05 was excluded from analysis due to a compliance less than 75%. Snore data of subject 10 got lost.

Table 3.13.: Compliance of subjects in regards to sleep parameter, snoring, BMI and blood pressure* analysis

Parameter per subject	01	02	03	04	05	06	07	08	09	10
Sleep parameters	100%	96%	100%	96%	71%	100%	96%	100%	100%	78%
Snoring	100%	89%	67%	96%	25%	100%	96%	100%	100%	-
BMI	100%	0%	100%	50%	50%	50%	100%	100%	25%	0%
BP*	100%	25%	100%	25%	0%	50%	100%	100%	0%	0%

3.3.2. Parameter Quantification

For analysis of quantified parameters, the focus was placed on differences between subjective estimations and objective measurements. The raw data for calculations performed in this subsection can be seen in Appendix D.2.

Sleep Parameter Analysis

In order to compare subjective and objective values, the arithmetic mean of all measurements within one week was computed. According to Table 3.14, subject 03 and 10 showed the largest difference of total sleep latency associated with a high variation of data due to limited collected data of only three weeks monitoring. Subject 04 was excluded from calculation as no subjective estimated data was available. For subject 10 there was no subjective estimated data in week 3 available.

Table 3.14.: Average difference and standard deviation of subjective estimation and objective measurements of sleep latency

Subject	Sleep latency			Overall sleep latency
	Week 1	Week 2	Week 3	
01	0.2 ± 1.3	1.6 ± 0.5	20.8 ± 1.2	5.9 ± 9.9
02	9.2 ± 1.3	7.8 ± 4.1	16.4 ± 3.0	8.9 ± 5.9
03	21.3 ± 1.6	11.5 ± 0.5	37.9 ± 2.5	18.4 ± 15.0
06	0.8 ± 2.2	2.8 ± 3.4	0.9 ± 1.1	2.6 ± 2.4
07	0.8 ± 1.6	0.6 ± 5.9	0.2 ± 1.6	2.2 ± 3.2
08	21.6 ± 1.0	0.4 ± 5.4	3.3 ± 1.2	8.3 ± 9.4
09	2.1 ± 4.7	5.1 ± 2.1	1.1 ± 7.4	4.3 ± 3.6
10	5.5 ± 3.8	96.2 ± 7.8	-	37.2 ± 51.1

The average difference and standard variation of sleep duration and efficiency can be seen in Table 3.15 and 3.16, respectively.

Table 3.15.: Average difference and standard deviation of subjective estimation and objective measurements of sleep duration

Subject	Sleep duration			Overall sleep duration
	Week 1	Week 2	Week 3	
01	0.3 ± 1.1	0.2 ± 1.0	0.1 ± 1.4	0.4 ± 0.4
02	0.0 ± 0.9	0.2 ± 1.0	1.6 ± 1.5	1.0 ± 1.0
03	0.2 ± 0.9	1.5 ± 1.5	1.6 ± 1.2	1.6 ± 1.1
06	1.1 ± 0.7	1.8 ± 1.1	0.3 ± 0.3	2.3 ± 2.5
07	0.3 ± 1.1	0.7 ± 1.0	1.7 ± 1.3	2.4 ± 3.1
08	0.5 ± 0.7	0.4 ± 0.5	0.5 ± 0.4	2.3 ± 3.8
09	0.0 ± 0.9	0.8 ± 0.7	1.8 ± 3.4	2.9 ± 4.1
10	0.4 ± 0.9	0.8 ± 1.5	-	3.7 ± 5.4

Table 3.16.: Average difference and standard deviation of subjective estimation and objective measurements of sleep efficiency

Subject	Sleep efficiency			Overall sleep efficiency
	Week 1	Week 2	Week 3	
01	9.2 ± 1.7	5.4 ± 4.2	16.4 ± 7.0	8.0 ± 6.5
02	5.9 ± 2.7	8.5 ± 1.8	4.3 ± 3.6	5.2 ± 2.7
03	9.4 ± 2.8	3.1 ± 2.5	20.9 ± 2.8	9.1 ± 8.4
06	19.0 ± 1.9	3.4 ± 5.0	9.4 ± 1.4	9.5 ± 6.8
07	9.1 ± 0.5	3.0 ± 1.8	8.3 ± 0.8	6.9 ± 2.7
08	16.3 ± 0.5	3.8 ± 1.4	7.4 ± 0.3	8.9 ± 5.3
09	5.2 ± 3.9	4.8 ± 2.7	9.2 ± 10.5	7.1 ± 2.4
10	6.2 ± 3.1	4.8 ± 2.3	-	7.0 ± 2.7

The average difference and standard deviation of the sleep parameters with min-max values [min value, max value] were: Sleep latency of 11.7 ± 20.8 minutes [0.2, 96.2], sleep duration of 0.7 ± 0.6 hours [0.0, 1.8] and sleep efficiency of 8.4 ± 5.1 % [3.0, 20.9].

Exemplarily, the course of the objective and subjective recorded sleep latency, sleep duration and sleep efficiency of subject 03 is illustrated in Figure 3.14, 3.13 and 3.14, respectively.

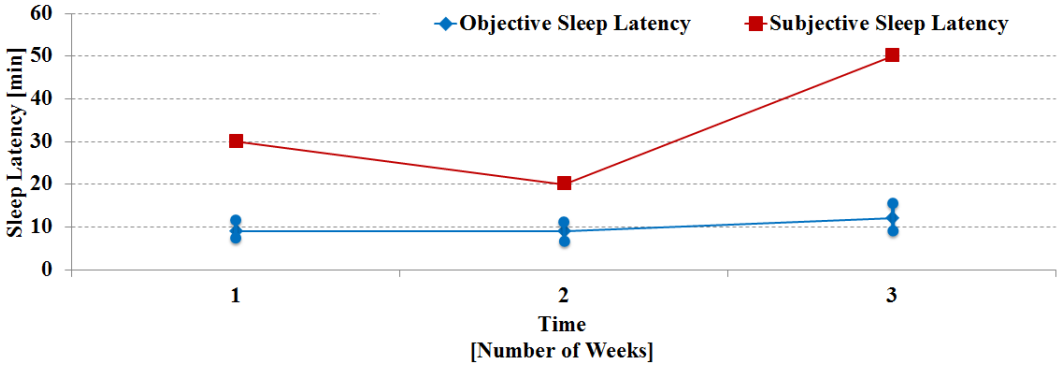

Figure 3.12.: Subjective and average objective sleep latency of subject 03

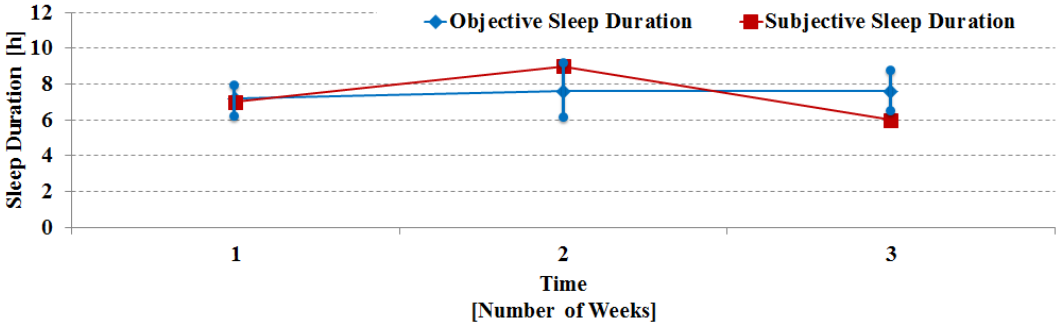

Figure 3.13.: Subjective and average objective sleep duration of subject 03

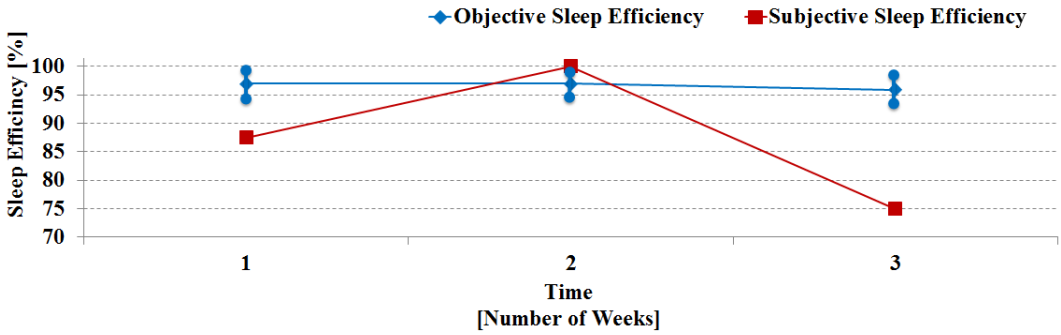

Figure 3.14.: Subjective and average objective sleep efficiency of subject 03

Snore Analysis

Table 3.17.: Arithmetic mean and standard deviation of snoring rate per subject

Subject	Snore rate				Overall snore rate
	Week 1	Week 2	Week 3	Week 4	
01	1.7 ± 1.7	0.9 ± 1.9	0.7 ± 1.5	0.0 ± 0.0	0.8 ± 0.7
02	2.2 ± 0.8	0.4 ± 0.8	0.5 ± 0.5	1.0 ± 1.7	1.0 ± 0.8
04	13.8 ± 13.7	10.7 ± 11.2	2.9 ± 2.5	8.7 ± 8.4	9.0 ± 4.6
06	15.9 ± 3.9	25.9 ± 17.8	43.3 ± 9.4	26.6 ± 12.0	27.9 ± 11.4
07	2.5 ± 4.0	8.7 ± 7.8	3.6 ± 2.6	1.6 ± 2.4	4.1 ± 3.2
08	9.0 ± 6.3	10.1 ± 5.0	5.6 ± 4.7	8.6 ± 4.4	8.3 ± 1.9
09	1.4 ± 1.9	0.9 ± 1.9	1.0 ± 1.9	1.7 ± 2.6	1.25 ± 0.4

The average value of the snoring rate of all 7 subjects was 7.5% (Table 3.17). Subject 06 and 08 showed values above this average and answered the item *Do you snore?* with *Yes*, indicating a matching. Subject 04 showed a value above the average as well, but answered all respective items with *No*. Subject 07 stated to snore during the feasibility study, showing a low average snore rate, but still having a high standard deviation. All other subjects recorded a low snoring rate, showing a matching with the answers to the respective item.

Table 3.18.: Responses of *RS* item *'Do you snore?'*

Subject	Response of *RS* item $\tilde{I}_1$			
	Week 1	Week 2	Week 3	Week 4
01	No	No	No	No
02	No	No	No	No
04	No	No	No	No
06	Yes	Yes	Yes	Yes
07	Yes	Yes	Yes	No
08	Yes	Yes	Yes	Yes
09	No	No	No	No

Subject 08 responded the *RS* item *How often do you snore?* always with the

same answer through all four weeks (Answer: *3 to 4 times a week*). The snore rate remained at the same average level during this period, except of week three where it decreased (Table 3.17). The course of the snore rate allowed a better comparison between the answers of the item and the measurements. Subject 06 answered week 1 and 4 with *one or two times a week* and week 2 and 3 with *nearly every day*. The course of the snore rate indicates an increase in the snore rate in week 2 and 3 (Figure 3.15). As all other subjects answered the question *Do you snore?* with *No*, they were never asked for *RS* item *How often do you snore?*.

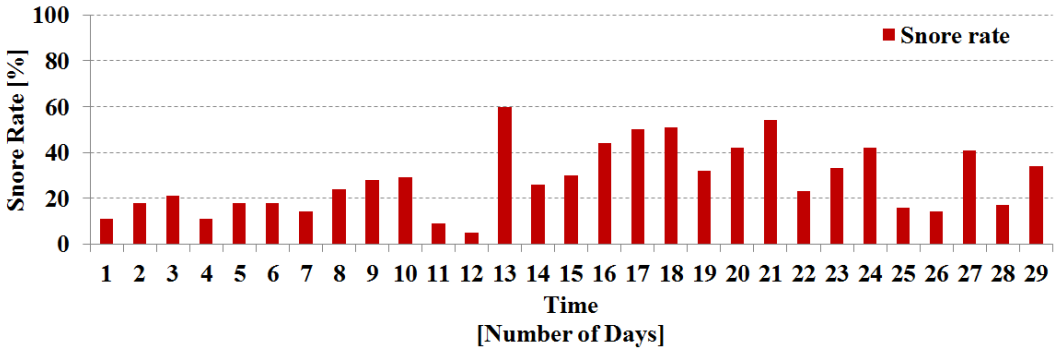

Figure 3.15.: Course of snore rate of subject 06

BMI Analysis

As a subject might have more than one weight value per week transferred, the values were averaged. Weekly and total arithmetic mean and standard deviation were calculated for each subject (Table 3.19) separately.

Table 3.19.: Start BMI, arithmetic mean and standard deviation of BMI per subject

Subject	BMI					Overall BMI
	Start	Week 1	Week 2	Week 3	Week 4	
01	22.6	22.1 ± 0.0	22.5 ± 0.0	22.2 ± 0.0	22.2 ± 0.0	22.3 ± 0.2
03	21.1	22.6 ± 0.1	20.8 ± 0.3	20.8 ± 0.2	21.0 ± 0.4	22.8 ± 0.2
07	23.4	23.3 ± 0.0	23.3 ± 0.0	23.4 ± 0.0	23.3 ± 0.0	23.3 ± 0.1
08	24.6	25.2 ± 0.0	25.2 ± 0.0	25.1 ± 0.0	25.2 ± 0.0	25.0 ± 0.2

Figure 3.16 illustrates exemplarily the recorded BMI of subject 03 over four weeks, showing small variances. A BMI value of 35 indicates a higher risk of OSA (Threshold in Figure 3.16). Corresponding to the measured results, no subject answered this item with "*Yes*".

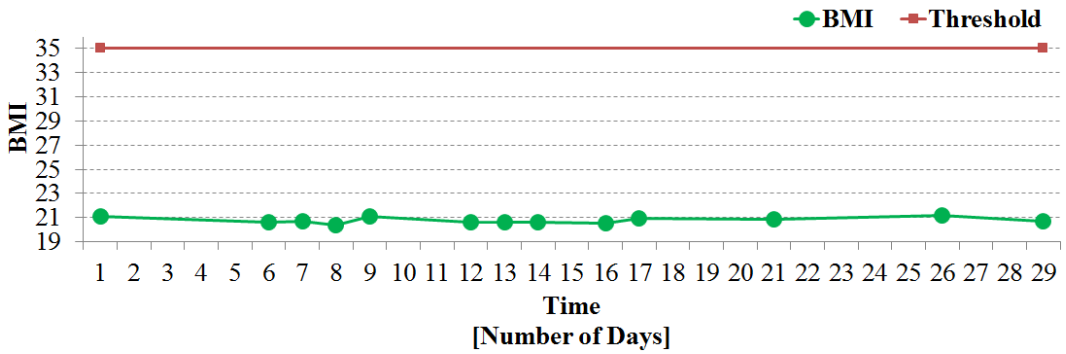

Figure 3.16.: Monitored BMI of subject 03

Blood Pressure Analysis

Arithmetic mean and standard deviation of systolic and diastolic blood pressure for four subjects, who met the required compliance, can be seen in Table 3.20 and 3.21, respectively. The corresponding *RS* items *Do you have high blood pressure?* (BQ, $\tilde{I}_9$) and *Do you have or are being treated for High Blood Pressure?* (STOP-BANG, $\tilde{I}_4$) were all answered with *No*.

Table 3.20.: Start value, arithmetic mean and standard deviation of systolic blood pressure* per subject

Subject	sys. BP*					Overall sys. BP*
	Start	Week 1	Week 2	Week 3	Week 4	
01	-	133.3 ± 11.2	130.0 ± 0.0	116.0 ± 0.0	134.0 ± 0.0	128.3 ± 8.4
03	-	119.0 ± 9.9	122.7 ± 16.2	112.7 ± 11.5	121.5 ± 7.8	119.0 ± 4.5
07	111.0	109.0 ± 0.0	110.0 ± 0.0	108.0 ± 0.0	110.0 ± 0.0	109.6 ± 1.1
08	-	121.0 ± 0.0	118.0 ± 0.0	124.0 ± 0.0	118.0 ± 0.0	120.3 ± 2.9

Table 3.21.: Start value, arithmetic mean and standard deviation of diastolic blood pressure* per subject

Subject	dia. BP*					Overall dia. BP*
	Start	Week 1	Week 2	Week 3	Week 4	
01	-	81.7 ± 11.0	80.0 ± 0.0	70.0 ± 0.0	72.0 ± 0.0	75.9 ± 5.8
03	-	64.0 ± 5.7	76.3 ± 8.5	71.7 ± 7.1	73.0 ± 1.4	71.3 ± 5.2
07	70.0	71.0 ± 0.0	72.0 ± 0.0	69.0 ± 0.0	72.0 ± 0.0	70.8 ± 1.3
08	-	66.0 ± 0.0	63.0 ± 0.0	82.0 ± 0.0	75.0 ± 0.0	71.5 ± 8.7

Recorded systolic and diastolic blood pressure of subject 03 were at health level (Figure 3.17).

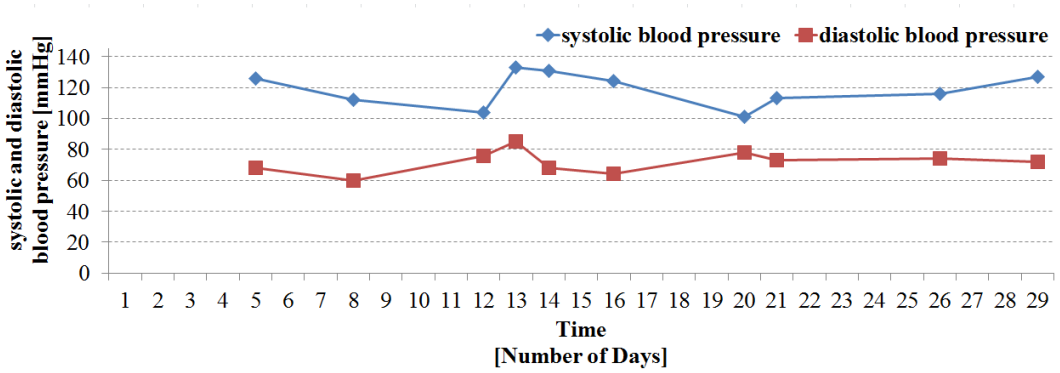

Figure 3.17.: Monitored systolic and diastolic blood pressure of subject 03

4. Discussion

A generic approach using standardized questionnaires to continually assess individuals' health state by applying the *Rolling Score Concept* is technically feasible. Modifications of questionnaires show less effect on time-related validation issues, due to the extracted *Score Mapping Rule Set*. Since there were differences between sensor data and corresponding responded items, quantification of items is a promising way to remove this incorrect character of subjective perception.

4.1. The *Rolling Score*

We applied the *Rolling Score Concept* to both, the combined and the single questionnaires and found minimal differences in the respective Global Scores. These differences may be caused by problems regarding natural variances of the questionnaire, the threshold or an absence of a clear answer. Figure 3.2 shows a deviation between the single and joined questionnaires. These deviations were caused, as the subject responded equal questions differently, maybe because the patient was unsure in answering or due to a lack of interest or 'hasty reading'. The threshold for scoring was set as

defined by the BQ, showing the best fit between the single and joined Global Scores. In general, the threshold had a small influence on the results, as a difference was found only in one subject (Figure 3.8). Still, this difference is in a substantial range (transition between high risk and low risk). However, as the results in Table 3.6 show, observed differences are in a reasonable range ($< 6\%$), we expect combining questionnaires and merging of items have a limited effect and may provide an approach for further simplification of a questionnaire. Still, analysis of merging was performed without using the gold standard, since standardized questionnaires were not validated for asking them every day.

The application of a specific *Time Schedule* to segment a standardized questionnaire may lead to a loss of time-related validation. As can be seen by the results in Table 3.5, this loss is compensable to a certain degree by the extracted *Score Mapping Rule Set*. Nevertheless, a certain deviation of the scores was found, caused by the variability of the categories *Sleep Disturbances* and *Daytime Somnolence*. The same variability caused a small temporal variance of the Global Scores, which was actually expected, since the involved *Rolling Score* categories (for instance: *frequent awakenings* or *going to the bathroom during sleep*) depend on the daily state and therefore may alternate strongly from week to week. The highest deviation was at 7.1% of the Global Scores of PSQI caused on the one hand by the categories referred to above, and on the other hand by the high granularity of the scoring system of PSQI (scoring range: 0 to 21). Compliance as exclusion criterion for risk evaluation and data analysis does not take into account the individual risk assessing characteristics of a screening questionnaire.

Therefore, the definition of an exclusion criteria set per questionnaire is reasonable, which gradually determines inclusion based on the current Global Score and a relative deviation.

Generally, deviations were not greater than 8%, suggesting that applying a specific *Time Schedule* to questions has only little influence on the validity of the Global Scores. Thus, the *Rolling Score Concept* has promising potential for continual screening of individuals' risk based on standardized questionnaires. However, further studies need to be done to verify the proposed risk assessment approach.

4.2. Classification and Merging

Generally, modification of a standardized questionnaire leads to a loss of validation, so that each changing step must be critically addressed to the characteristics of the standardized version. The definition of a *Score Mapping Rule Set* determines how processed items $\tilde{I}_i$ were mapped back to their original Item Score IS_i. As order and wording of questions are important aspects to provide respondents with equal stimulus [28], the *Content-related Context Rule* assures a grouping of items $\tilde{I}_i$ dealing with the same stimulus. This is important because respondents may feel irritated, shifting from one topic to another. Another important characteristic is the response format, which remained unchanged in the course of questionnaire processing. The response format should be designed in a way to enable the respondent to complete the questionnaire rapidly. As responses were adapted according to their application, some responses were cancelled, making it easier to rapidly

complete the interviewing process. Modifications regarding diverse time periods between items and their respective item score is considered by the *Temporal Context Rule*.

The exact definition of each question, the last characteristic of a standardized questionnaire, was considered during the merging of items. In sleep medicine the terms *daytime sleepiness* and *tiredness* have different meanings. *Tiredness* occurs in patients suffering from insomnia, describing a state in which a person is not able to fall asleep or to sleep through the night resulting in a fatigue during the day [32]. Nevertheless, affected patients cannot sleep during daytime. This feature distinguishes *tiredness* from *daytime sleepiness*, where the patient shows the inability to keep awake, especially in monotone situations like driving a vehicle over long distances [32]. This knowledge about specific definitions of items must be considered during the merging as was done in the *Rolling Score* category *Daytime Somnolence* (Appendix B.2).

The merging possibility of a disjunction was applied to questions from different questionnaires, showing a significant association, based on validation studies [33], as is illustrated in Table 3.10. Due to time aspects, a merging of items could be difficult. There are items showing time references in its question and others in its responses only. The *Score Mapping Rule Set* considers these differences of the time aspect applying a specific algorithm, as can be seen in the *Rolling Score* category *Daytime Somnolence* in Table 3.11.

4.3. Feasibility Study

Since subjects were instructed to use sensors for item quantification, sensor data may have had an influence on the answers of the corresponding items. This could have introduced bias into the scoring of questionnaires. A potential bias is in the range of ± 3 (ϵ_{rel} = 14.3%) according to the scoring system of PSQI. Nevertheless, differences were found between the subjective estimation and objective measurement of sleep efficiency, sleep duration and sleep latency regarding Table 3.16, 3.15 and 3.14. The *Withings*® sleep tracker was chosen for the study, due to a strong performance under free-living conditions [34] and the possibility of sleep data fetching by an API. Most noticeable is the difference of the sleep duration that was in general underestimated by 0.7 hours. The standard variation was high, generally caused by a weekly different estimation and the limited number of participants. Sleep efficiency and latency have statistically no considerable difference, still subjects have at some point clearly underestimated these parameters as can be seen for subject 03 in Figure 3.14 and 3.12.

The parameters *Snoring* and *Snore Frequency* were quantified by means of a snore application. A potential bias is in the range of ± 1 (ϵ_{rel} = 33.3%) according to the scoring system of BQ. There were several limitations on snore data analysis, due to the inaccurate definition of snoring with respect to objective measurements [35] and unknown uncertainties, based on the snore detection algorithm. The developer of the snore application was contacted for further information, but he refused cooperation. In addition, the deviation caused by different distances between the subject and the

microphone, as well as the angle must be taken into account. As the snore application was used as a closed system only, error estimation was not performed and would have gone beyond the scope of this thesis. However, more sophisticated algorithms combining the frequency and time domain are recommended for measurements of snoring [36]-[37]. The question *Do you snore?* cannot be answered precisely due to the lack of accurate definition of snoring. Therefore, comparison of measured snore rate (Table 3.17) with subjective estimations (Table 3.18) need to be handled carefully. Only information on a tendency towards snoring can be extracted from the course of the snore rate over time (Figure 3.15). Nevertheless, the uncertainty of the snore rate is unknown. Moreover, proper measurements of snoring based on the intensity level is not sufficient. For this reason a quantification of the parameter *Loudness of Snoring* remains pointless [36].

Other quantifiable parameters like the BMI and blood pressure were only asked every 28^{th} day. The BMI is a parameter showing only small fluctuations within a period of one month (Figure 3.16) and all values were at health level (Table 3.19). As this parameter has a strong effect on the scoring, regular measurements should be used to update the scoring, in particular for patients with instable medical condition. As expected, the measured systolic and diastolic blood pressure values indicate no hypertension (Table 3.20 and 3.21) and corresponded to the answers of the respective items. For diagnosing hypertension, regular blood pressure self-measurements are necessary which were not conducted during this field study. Figure 3.17 illustrates irregular self-measurements of blood pressure of subject 03. A bias of BMI and blood pressure was non expected, as all subjects were

healthy. For applying the concept to patients, a bias in the range of ± 1 (ϵ_{rel} = 33.3%) must be expected.

These quantified parameters could be used for a substitution of certain items. However, mapping these measurements to the scoring may require a specific algorithm. Another field of application might be a triggering of specific items collecting further information on a certain parameter. This may enhance awareness of the patient, improving compliance with the involved stakeholders.

Applying the concept to patients requires a revise of the mobile application. Implementation of a clear representation of the *Rolling Score* items is necessary for a correct understanding of questions and extraction of high quality data [38].

4.4. Conclusion and Outlook

Standardized questionnaires provide a concise, cost-effective and easy-to-use screening tool for rapid assessment of individuals' risk and health state. Applying self-rated questionnaires to mHealth-based telemonitoring systems enables continual risk assessment at home. The results show the technical feasibility of the *Rolling Score Concept* applied to the field of sleep medicine and deviations of scores caused by the *Time Schedule* are in a reasonable range (smaller than 8%). However, a general validation of the concept in a patient collective has to be approved in order to confirm the diagnostic benefit. As quantifiable parameters were found, sensor data could be applied for substitution of corresponding items. Although, these

measurements cannot directly be used for scoring and future employment will show how sensor data should be considered in the *Rolling Score Concept*. In future work, embedding the *Rolling Score Concept* in a collaborative network for congestive heart failure patients will be performed in order to gain real world experiences with this new method for continual risk assessment.

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Appendix

Appendix A.

Feasibility Study - Subject Information

Informed consent

Proband name (in block letters): ……..

I hereby declare my consent to participate in the field study of the technical feasibility of **SleepMemory** performed at the AIT Austrian Institute of Technology in the course of Claudio Zluga's Master Thesis.

I agree that all determined data in relation to this field study is collected in non-personal (pseudonymised) form and used for scientific purpose.

Data collection:

During the field study a sleep tracker collects and stores sleep-related data based on accelerometry. The data is sent to the Withings server and is retrieved daily by AIT servers.

A snore app records acoustic signals (acoustic pressure profile) over night and stores it as a 3GP-file on the local storage of the smartphone. After the extraction of the characteristic parameters of the acoustic pressure profile, these files have to be deleted by the user himself (see workflow sheet). To avoid reconstruction of the data, the entire storage of the smartphone will be deleted at the end of the field study.

I hereby declare my consent that these parameters together with my age, BMI (Body Mass Index) and gender will be recorded, stored and might be used for data analysis, but I reserve the right to terminate my voluntary participation at any time.

I received a copy of this informed consent. The original remains at AIT.

……

(Date and signature of the proband)

(The proband receives a signed copy of the informed consent, the original remains in the directory of the master student)

Subject:……**Testuser01**…..…….....

TODOs when going to bed:

- ✓ **Check, if questions are answered**
- ✓ **Put on and activate Withings-Wristband (not waterproof!)**
- ✓ **Connect phone to the charger and activate „SnoreClock“-App**

TODOs when standing up:

- ✓ **Deactivate Withings**
  - Press powerbutton -> Swipe „Off“ to the right
  - Start „Withings“-app
  - Close app after synchronization
  - Take off Withings
- ✓ **Deactivate Snore-App**
  - Start „SnoreClock“-app
  - Tip on the red button and confirm
  - CSV-Export
  - Delete 3GP-file
- ✓ **Answer questions**
- ✓ **Weighing once a week**
- ✓ **Blood pressure measurement once a week**

Workflow

Sleep Tracker:

- Put the sleep tracker on the wrist
- Press powerbutton to the top right (Withings starts)
- Tip on the moon symbol and swipe „on“ to the left (sleeptracking starts)

- Press powerbutton and swipe „Off“ to the right
- Application **„Withings“** starts: Control of data transmission
- Charge sleeptracker every 5 days

If Withings **does not** synchronize -> go to Settings -> Applications -> Scroll down to „**Withings**“ -> Open and execute button „Force stop“ -> now synchronize manually: Open app and press powerbutton on the sleeptracker for 3-sec.

Application „SnoreClock“:

- Open application and tip on the red button to start the record
- Put the smartphone beside your bed (Screen downwards)
- Align microphone (bottom of smartphones) towards your body

- Tip on red button again to stop record
- Tip on menu (top left, three bars)
- Tip on register „**Statistics**“ – „**›**“ symbol
- Go to current statistics and press on until a window pops up
- Tip on „**Export csv**“ and close any popping up window
- Press again on current statistics: tip on „**delete record“**

As the internal memory is full after 10 days, deleting files is necessary to continue the study. After returning the smartphone, the coordinator will delete the internal memory with an appropriate algorithm to ensure reconstruciton of 3GP-files is impossible. If ones open the app again, the statistic is shown -> Arrow to the top left returns to the main screen. Now the measurement can be conducted again.

Application „Cardiac Rehab“:

This application is used for pushing the questions to the user within the monitoring period. The questions are available through the application interface itself or by notifications (swipe from top to the bottom on display). In the app „Cardiac Rehab“ appears a tile, which opens the pushed questionnaire by tipping. In order to check if the questions are answered accordingly, the application offers the tile „*Observations*“ (Date and Time).

Measurement of weight and blood pressure: The parameters weight, bloodpressure and heart rate can be measured through NFC-enabled weighing scales and blood pressure monitors. To do so, perform measurement and then put the smartphone on the device to transfer data. Click on„*Save*“ and close app.

Appendix B.

Identification and Merging of Items

B.1. Identified Items

The corresponding class IDs were: *Snoring* = 1, *Daytime Somnolence* = 2, *Quantifiable Parameters* = 3, *Age/Gender* = 4, *Sleep Disturbances* = 5, *Sleep Quality* = 6 and *Sleep Medication* = 7.

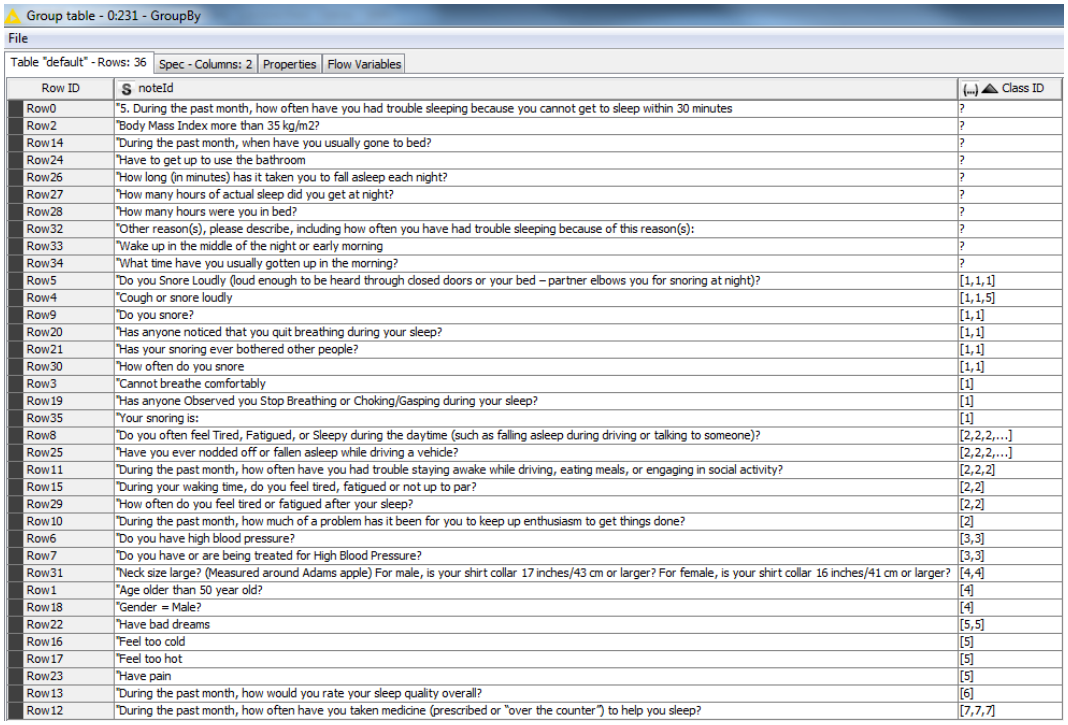
B.2. Merged Items

Merging possibility ***Replacement***

Origin *replacing* Item	**Origin *replaced* Item**	***RS* Item**
Do you have or are being treated for High Blood Pressure? (STOP-BANG, I_4) o Yes o No	Do you have high blood pressure? (BQ, I_9) o Yes o No o Don't know	Do you have or are being treated for High Blood Pressure? ($\tilde{I}_{23}$) o Yes o No o Don't know
During your waking time, do you feel tired, fatigued or not up to par? (BQ, I_7) o Nearly every day o 3-4 times a week o 1-2 times a week o 1-2 times a month o Never or nearly never	During the past four weeks, how much of a problem has it been for you to keep up enough enthusiasm to get things done? (PSQI, I_9) o No problem at all o Only a very slight problem o Somewhat of a problem o A very big problem	During your waking time, do you feel tired, fatigued or not up to par? ($\tilde{I}_{15}$) o Nearly every day o 3-4 times a week o 1-2 times a week - o Never or nearly never
During your waking time, do you feel tired, fatigued or not up to par? (BQ, I_7) o Nearly every day o 3-4 times a week o 1-2 times a week o 1-2 times a month o Never or nearly never	Do you often feel Tired, Fatigued, or Sleepy during the daytime (such as falling asleep during driving or talking to someone)? (STOP-BANG, I_2) o Yes o No	During your waking time, do you feel tired, fatigued or not up to par? ($\tilde{I}_{15}$) o Nearly every day o 3-4 times a week o 1-2 times a week - o Never or nearly never
Have you ever nodded off or fallen asleep while driving a vehicle? (BQ, I_8) o Yes o No	Do you often feel Tired, Fatigued, or Sleepy during the daytime (such as falling asleep during driving or talking to someone)? (STOP-BANG, I_2) o Yes o No	Have you ever nodded off or fallen asleep while driving a vehicle? ($\tilde{I}_{16}$) o Yes o No

Merging possibility ***Disjunction***

Origin *replacing* Item	**Origin *disjuncted* Item**	***RS* Item**
Has anyone noticed that you quit breathing during your sleep? (BQ, I_5) o Nearly every day o 3-4 times a week o 1-2 times a week o 1-2 times a month o Never or nearly never	Has anyone Observed you Stop Breathing or Choking/Gasping during your sleep? (STOP-BANG, I_3) o Yes o No	Has anyone noticed that you quit breathing or suffer from breathing problems (Choking/Gasping) during your sleep? ($\tilde{I}_4$) o Nearly every day o 3-4 times a week o 1-2 times a week - o Never or nearly never
Has anyone noticed that you quit breathing during your sleep? (BQ, I_5) o Nearly every day o 3-4 times a week o 1-2 times a week o 1-2 time a month o Never or nearly never	During the past four weeks, how often have you had trouble sleeping because you cannot breathe comfortably? (PSQI, I_8) o Not at all o Less than once a week o Once or twice a week o Three or more times a week	Has anyone noticed that you quit breathing or suffer from breathing problems (Choking/Gasping) during your sleep? ($\tilde{I}_4$) o Nearly every day o 3-4 times a week o 1-2 times a week - o Never or nearly never
Your snoring is: (BQ, I_2) o Slightly louder than breathing o As loud as talking o Louder than talking o Very loud - can be heard in adjacent rooms	Do you Snore Loudly (loud enough to be heard through closed doors or your bed-partner elbows you for snoring at night)? (STOP-BANG, I_1) o Yes o No	Your snoring is: ($\tilde{I}_2$) o Slightly louder than breathing o As loud as talking o Louder than talking o Very loud - can be heard in adjacent rooms o Loud enough so that other people are bothered by your snoring
Your snoring is: (BQ, I_2) o Slightly louder than breathing o As loud as talking o Louder than talking o Very loud - can be heard in adjacent rooms	Has your snoring ever bothered other people? (BQ, I_4) o Yes o No	Your snoring is: ($\tilde{I}_2$) o Slightly louder than breathing o As loud as talking o Louder than talking o Very loud - can be heard in adjacent rooms o Loud enough so that other people are bothered by your snoring


Group table - 0:231 - GroupBy

File

Table "default" - Rows: 36 | Spec - Columns: 2 | Properties | Flow Variables

Row ID	noteId	Class ID
Row0	"5. During the past month, how often have you had trouble sleeping because you cannot get to sleep within 30 minutes	?
Row2	"Body Mass Index more than 35 kg/m2?	?
Row14	"During the past month, when have you usually gone to bed?	?
Row24	"Have to get up to use the bathroom	?
Row26	"How long (in minutes) has it taken you to fall asleep each night?	?
Row27	"How many hours of actual sleep did you get at night?	?
Row28	"How many hours were you in bed?	?
Row32	"Other reason(s), please describe, including how often you have had trouble sleeping because of this reason(s):	?
Row33	"Wake up in the middle of the night or early morning	?
Row34	"What time have you usually gotten up in the morning?	?
Row5	"Do you Snore Loudly (loud enough to be heard through closed doors or your bed – partner elbows you for snoring at night)?	[1,1,1]
Row4	"Cough or snore loudly	[1,1,5]
Row9	"Do you snore?	[1,1]
Row20	"Has anyone noticed that you quit breathing during your sleep?	[1,1]
Row21	"Has your snoring ever bothered other people?	[1,1]
Row30	"How often do you snore	[1,1]
Row3	"Cannot breathe comfortably	[1]
Row19	"Has anyone Observed you Stop Breathing or Choking/Gasping during your sleep?	[1]
Row35	"Your snoring is:	[1]
Row8	"Do you often feel Tired, Fatigued, or Sleepy during the daytime (such as falling asleep during driving or talking to someone)?	[2,2,2,...]
Row25	"Have you ever nodded off or fallen asleep while driving a vehicle?	[2,2,2,...]
Row11	"During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?	[2,2,2]
Row15	"During your waking time, do you feel tired, fatigued or not up to par?	[2,2]
Row29	"How often do you feel tired or fatigued after your sleep?	[2,2]
Row10	"During the past month, how much of a problem has it been for you to keep up enthusiasm to get things done?	[2]
Row6	"Do you have high blood pressure?	[3,3]
Row7	"Do you have or are being treated for High Blood Pressure?	[3,3]
Row31	"Neck size large? (Measured around Adams apple) For male, is your shirt collar 17 inches/43 cm or larger? For female, is your shirt collar 16 inches/41 cm or larger?	[4,4]
Row1	"Age older than 50 year old?	[4]
Row18	"Gender = Male?	[4]
Row22	"Have bad dreams	[5,5]
Row16	"Feel too cold	[5]
Row17	"Feel too hot	[5]
Row23	"Have pain	[5]
Row13	"During the past month, how would you rate your sleep quality overall?	[6]
Row12	"During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?	[7,7,7]

Figure B.1.: Classification outcome of all questionnaires

Appendix C.

Processed Questionnaires

Rolling Score Concept applied to BQ

***RS* Category**	***RS* Item**	***IS***
Snoring ($\tilde{C}_1$)	Do you snore? ($\tilde{I}_1$)	(1)
	o Yes	(0)
	o No	(0)
	o Don't know	
	Your snoring is: ($\tilde{I}_2$)	(0)
	o Slightly louder than breathing	(0)
	o As loud as talking	(1)
	o Louder than talking	(1)
	o Very loud - can be heard in adjacent rooms	
	How often do you snore? ($\tilde{I}_3$)	(1)
	o Nearly every day	(1)
	o 3-4 times a week	(0)
	o 1-2 times a week	(0)
	o Never or nearly never	
	Has your snoring ever bothered other people? ($\tilde{I}_4$)	(1)
	o Yes	(0)
	o No	
	Has anyone noticed that you quit breathing during your sleep? ($\tilde{I}_5$)	
	o Nearly every day	(1)
	o 3-4 times a week	(1)
	o 1-2 times a week	(0)
	o Never or nearly never	(0)
Daytime Somnolence ($\tilde{C}_2$)	How often do you feel tired or fatigued after your sleep? ($\tilde{I}_6$)	
	o Nearly every day	(1)
	o 3-4 times a week	(1)
	o 1-2 times a week	(0)
	o Never or nearly never	(0)
	During your waking time, do you feel tired, fatigued or not up to par? ($\tilde{I}_7$)	
	o Nearly every day	(1)
	o 3-4 times a week	(1)
	o 1-2 times a week	(0)
	o Never or nearly never	(0)
	Have you ever nodded off or fallen asleep while driving a vehicle? ($\tilde{I}_8$)	
	o Yes	(1)
	o No	(0)
Monthly Quantifiable ($\tilde{C}_3$)	Do you have high blood pressure? ($\tilde{I}_9$)	
	o Yes	(1)
	o No	(0)
	o Don't know	(0)

Rolling Score Concept applied to STOP-BANG

***RS* Category**	***RS* Item**	***IS***
Snoring ($\tilde{C}_1$)	Do you Snore Loudly (loud enough to be heard through closed doors or your bed-partner elbows you for snoring at night)? ($\tilde{I}_1$)	
	o Yes	(1)
	o No	(0)
	Has anyone Observed you Stop Breathing or Choking/Gasping during your sleep? ($\tilde{I}_2$)	
	o Yes	(1)
	o No	(0)
Daytime Somnolence ($\tilde{C}_2$)	Do you often feel Tired, Fatigued, or Sleepy during the daytime (such as falling asleep during driving or talking to someone)? ($\tilde{I}_3$)	
	o Yes	(1)
	o No	(0)
Monthly Quantifiable ($\tilde{C}_3$)	Do you have or are being treated for High Blood Pressure? ($\tilde{I}_4$)	
	o Yes	(1)
	o No	(0)
	Neck size large? (Measured around Adams apple) For male, is your shirt collar 17 inches/43 cm or larger? For female, is your shirt collar 16 inches/41 cm or larger? ($\tilde{I}_5$)	
	o Yes	(1)
	o No	(0)
	Body Mass Index more than 35 kg/m²? ($\tilde{I}_6$)	
	o Yes	(1)
	o No	(0)
Age/Gender ($\tilde{C}_4$)	Age? Older than 50 years old? ($\tilde{I}_7$)	
	o Yes	(1)
	o No	(0)
	Gender = Male? ($\tilde{I}_8$)	
	o Yes	(1)
	o No	(0)

Rolling Score Concept applied to PSQI

***RS* Category**	***RS* Item**	***IS***
Sleep Disturbances ($\tilde{C}_1$)	During the past week, how often have you had trouble sleeping because you ...	
	... wake up in the middle of the night or early morning ? ($\tilde{I}_1$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... have to get up to use the bathroom? ($\tilde{I}_2$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	… cannot breathe comfortably? ($\tilde{I}_3$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... cough or snore loudly? ($\tilde{I}_4$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... feel too cold? ($\tilde{I}_5$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... feel too hot? ($\tilde{I}_6$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... had bad dreams? ($\tilde{I}_7$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... have pain? ($\tilde{I}_8$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... Other reason(s)? Please describe:	
	During the past week, how often have you had trouble sleeping because of this described reason(s)? ($\tilde{I}_9$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
Sleep Medication ($\tilde{C}_2$)	During the past week, how often have you taken sleep medicine (prescribed or 'over the counter') to help you sleep? ($\tilde{I}_{10}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
Daytime Somnolence ($\tilde{C}_3$)	During the past week, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity? ($\tilde{I}_{11}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	During the past week, how much of a problem has it been for you to keep up enough enthusiasm to get things done? ($\tilde{I}_{12}$)	
	o No problem at all	(0)
	o Only a very slight problem	(1)
	o Somewhat of a problem	(2)
	o A very big problem	(3)
Weekly Quantifiable ($\tilde{C}_4$)	During the past week, when have you usually gone to bed at night? Usual bed time (HH:MM): ($\tilde{I}_{13}$)	-
	During the past week, how long (in minutes) has it usually take you to fall asleep each night? Number in minutes (MM): ($\tilde{I}_{14}$)	-
	During the past week, when have you usually gotten up in the morning? Usual getting up time (HH:MM): ($\tilde{I}_{15}$)	-
	During the past week, how many hours of actual sleep did you get at night? Hours of sleep per night (HH): ($\tilde{I}_{16}$)	-
	During the past week, how often have you had trouble sleeping because you cannot get to sleep within 30 minutes? ($\tilde{I}_{17}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
Sleep Quality ($\tilde{C}_5$)	During the past four weeks, how would you rate your sleep quality overall? ($\tilde{I}_{18}$)	
	o Very good	(0)
	o Fairly good	(1)
	o Fairly bad	(2)
	o Very bad	(3)

Rolling Score Concept applied to BQ, STOP-BANG and PSQI

***RS* Category**	***RS* Item**	***IS***
Snoring ($\tilde{C}_1$)	Do you snore? ($\tilde{I}_1$)	
	o Yes	(1)
	o No	(0)
	o Don't know	(0)
	Your snoring is: ($\tilde{I}_2$)	
	o Slightly louder than breathing	(0)
	o As loud as talking	(0)
	o Louder than talking	(1)
	o Very loud - can be heard in adjacent rooms	(1)
	o Loud enough so that other people are bothered by your snoring	(1)
	How often do you snore? ($\tilde{I}_3$)	
	o Nearly every day	(1)
	o 3-4 times a week	(1)
	o 1-2 times a week	(0)
	o Never or nearly never	(0)
	Has anyone noticed that you quit breathing or suffer from breathing problems (Choking/Gasping) during your sleep? ($\tilde{I}_4$)	
	o Nearly every day	(1)
	o 3-4 times a week	(1)
	o 1-2 times a week	(0)
	o Never or nearly never	(0)
Sleep Disturbances ($\tilde{C}_2$)	During the past week, how often have you had trouble sleeping because you ...	
	... wake up in the middle of the night or early morning ? ($\tilde{I}_5$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... have to get up to use the bathroom? ($\tilde{I}_6$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... cough or snore loudly? ($\tilde{I}_7$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... feel too cold? ($\tilde{I}_8$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... feel too hot? ($\tilde{I}_9$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... had bad dreams? ($\tilde{I}_{10}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... have pain? ($\tilde{I}_{11}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
	... Other reason(s)? Please describe:	
	During the past week, how often have you had trouble sleeping because of this described reason(s)? ($\tilde{I}_{12}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
Sleep Medication ($\tilde{C}_3$)	During the past week, how often have you taken sleep medicine (prescribed or 'over the counter') to help you sleep? ($\tilde{I}_{13}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
Daytime Somnolence ($\tilde{C}_4$)	How often do you feel tired or fatigued after your sleep? ($\tilde{I}_{14}$)	
	o Nearly every day	(1)
	o 3-4 times a week	(1)
	o 1-2 times a week	(0)
	o Never or nearly never	(0)
	During your waking time, do you feel tired, fatigued or not up to par? ($\tilde{I}_{15}$)	
	o Nearly every day	(1)
	o 3-4 times a week	(1)
	o 1-2 times a week	(0)
	o Never or nearly never	(0)

	Have you ever nodded off or fallen asleep while driving a vehicle? ($\tilde{I}_{16}$)	
	o Yes	(1)
	o No	(0)
	During the past week, how often have you had trouble staying awake while eating meals, or engaging in social activity? ($\tilde{I}_{17}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
Weekly Quantifiable ($\tilde{C}_5$)	During the past week, when have you usually gone to bed at night? Usual bed time (HH:MM): ($\tilde{I}_{18}$)	-
	During the past week, how long (in minutes) has it usually take you to fall asleep each night? Number in minutes (MM): ($\tilde{I}_{19}$)	-
	During the past week, when have you usually gotten up in the morning? Usual getting up time (HH:MM): ($\tilde{I}_{20}$)	-
	During the past week, how many hours of actual sleep did you get at night? Hours of sleep per night (HH): ($\tilde{I}_{21}$)	-
	During the past week, how often have you had trouble sleeping because you cannot get to sleep within 30 minutes? ($\tilde{I}_{22}$)	
	o Not at all	(0)
	o Once or twice a week	(2)
	o Three or more times a week	(3)
Monthly Quantifiable ($\tilde{C}_6$)	Do you have or are being treated for High Blood Pressure? ($\tilde{I}_{23}$)	
	o Yes	(1)
	o No	(0)
	Neck size large? (Measured around Adams apple) For male, is your shirt collar 17 inches/43 cm or larger? For female, is your shirt collar 16 inches/41 cm or larger? ($\tilde{I}_{24}$)	
	o Yes	(1)
	o No	(0)
	Body Mass Index more than 35 kg/m²? ($\tilde{I}_{25}$)	
	o Yes	(1)
	o No	(0)
Sleep Quality ($\tilde{C}_7$)	During the past four weeks, how would you rate your sleep quality overall? ($\tilde{I}_{26}$)	
	o Very good	(0)
	o Fairly good	(1)
	o Fairly bad	(2)
	o Very bad	(3)
Age/Gender ($\tilde{C}_8$)	Age? Older than 50 years old? ($\tilde{I}_{27}$)	
	o Yes	(1)
	o No	(0)
	Gender = Male? ($\tilde{I}_{28}$)	
	o Yes	(1)
	o No	(0)

Appendix D.

Feasibility Study - Data

D.1. Compliance

Table D.1.: Sent, received and missing *RS* categories and compliance of subjects

Subject	*RS* Categories sent	*RS* Categories received	*RS* Categories missing	Compliance
01	44	44	0	100%
02	44	44	0	100%
03	44	44	0	100%
04	48	36	12	75%
05	48	38	10	79%
06	47	46	1	98%
07	46	46	0	100%
08	47	45	2	96%
09	47	35	12	75%
10	48	42	6	88%

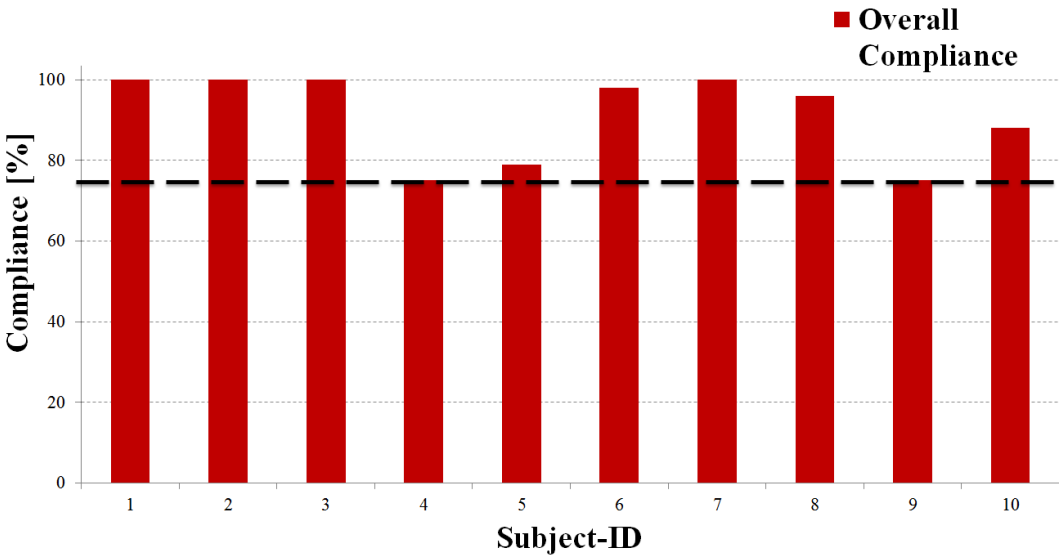


Figure D.1.: Total compliance per subject

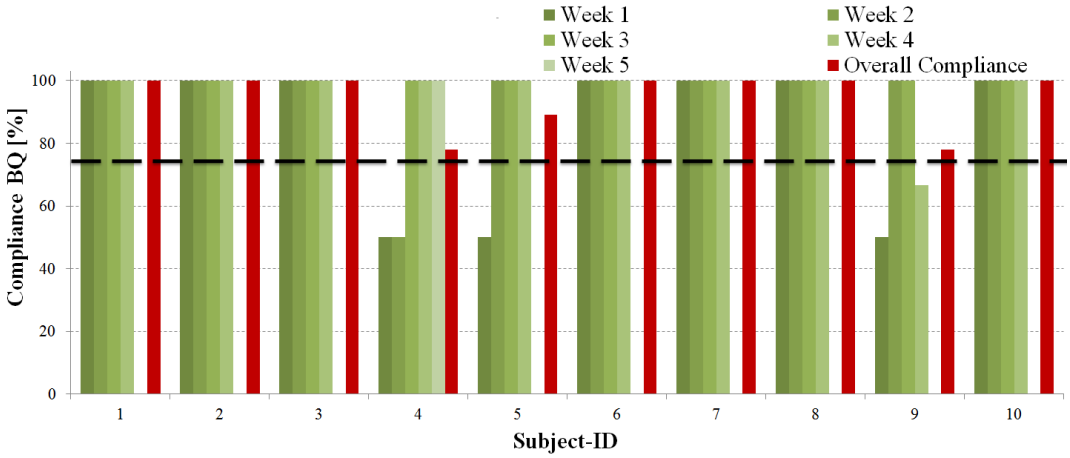


Figure D.2.: Compliance of BQ

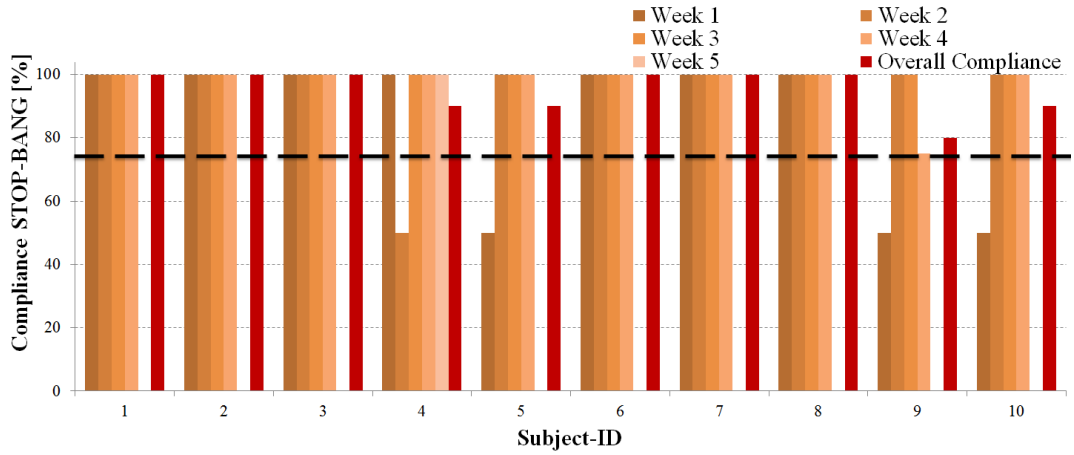


Figure D.3.: Compliance of STOP-BANG

D.2. Raw Data for Quantified Parameters

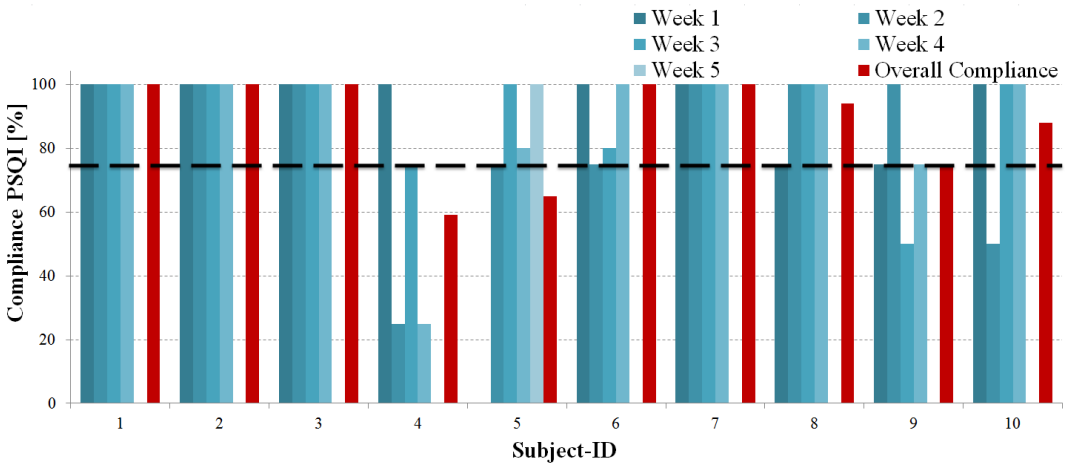


Figure D.4.: Compliance of PSQI

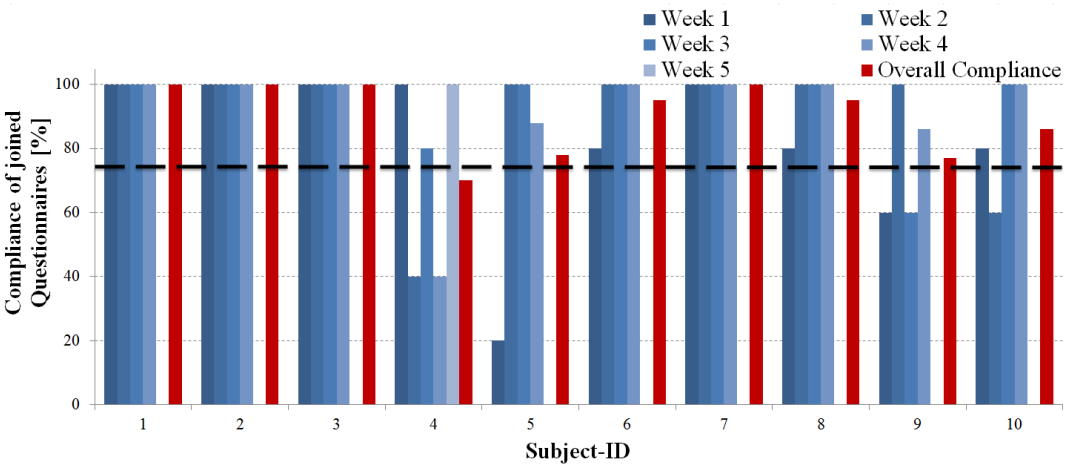


Figure D.5.: Compliance of joined questionnaires

Username	Subjective Sleep Duration	Subjective Sleep Efficiency	Subjective Sleep Latency	Mean Sleep Duration	Mean Sleep Latency	Mean Sleep Efficiency
Subject 01	8	88.889	10	8.204	8.4	94.31
Subject 01	7	77.778	30	7.133	9.167	94.142
Subject 01	7	87.5	10	7.274	9.8	96.652
Subject 02	7	87.5	20	6.77	12.167	95.987
Subject 02	9	90	30	7.401	13.571	94.53
Subject 02	8	88.889	20	8.048	10.8	94.752
Subject 03	9	100	20	7.55	8.5	96.887
Subject 03	6	75	50	7.563	12.143	95.884
Subject 03	7	87.5	30	7.171	8.714	96.944
Subject 05	8	72.727	15	7.425	12.25	91.8
Subject 05	11	110	20	7.552	21.75	93.08
Subject 05	6	85.714	40	7.496	10.6	95.764
Subject 06	7	77.778	10	8.105	10.833	96.755
Subject 06	9	90	5	7.185	7.833	93.36
Subject 06	7	87.5	10	7.314	9.143	96.914
Subject 07	8	88.889	10	7.716	9.2	98.022
Subject 07	8	100	10	7.252	10.6	97.016
Subject 07	8	88.889	10	6.265	9.833	97.205
Subject 08	8	114.286	30	7.456	8.4	97.964
Subject 08	7.5	93.75	10	7.122	10.4	97.594
Subject 08	7.25	90.625	5	6.753	8.333	97.98
Subject 09	7	100	7	7.037	9.143	94.759
Subject 09	7	87.5	7	6.191	12.143	92.274
Subject 09	7	100	11	5.167	9.857	90.847
Subject 10	8	88.889	15	8.43	9.5	95.072
Subject 10	8	88.889	107	7.21	10.833	93.668

Figure D.6.: Raw data (part 1) of sleep parameters

Sleep Duration Diff	Sleep Latency Diff	Sleep Efficiency Diff	SD Sleep Efficiency	SD Sleep Latency	SD Sleep Duration	Time of Observation
0.204	1.6	5.421	4.169	0.548	0.961	25.Dez.2015
0.133	20.833	16.364	7.022	1.169	1.401	01.Jan.2016
0.274	0.2	9.152	1.74	1.304	1.059	25.Dez.2015
0.23	7.833	8.487	1.751	4.119	0.959	25.Dez.2015
1.599	16.429	4.53	3.612	3.047	1.482	01.Jan.2016
0.048	9.2	5.863	2.725	1.304	0.935	25.Dez.2015
1.45	11.5	3.113	2.462	0.548	1.496	25.Dez.2015
1.563	37.857	20.884	2.82	2.545	1.187	01.Jan.2016
0.171	21.286	9.444	2.782	1.604	0.908	25.Dez.2015
0.575	2.75	19.073	2.266	7.228	0.875	25.Dez.2015
3.448	1.75	16.92	3.912	15.65	2.281	01.Jan.2016
1.496	29.4	10.05	3.536	2.608	1.51	08.Jan.2016
1.105	0.833	18.977	1.895	2.229	0.74	25.Dez.2015
1.815	2.833	3.36	5.025	3.43	1.092	01.Jan.2016
0.314	0.857	9.414	1.357	1.069	0.352	08.Jan.2016
0.284	0.8	9.133	0.464	1.643	1.102	25.Dez.2015
0.748	0.6	2.984	1.806	5.899	1.023	01.Jan.2016
1.735	0.167	8.316	0.799	1.602	1.311	08.Jan.2016
0.544	21.6	16.322	0.509	0.894	0.734	25.Dez.2015
0.378	0.4	3.844	1.357	5.413	0.464	01.Jan.2016
0.497	3.333	7.355	0.307	1.211	0.433	08.Jan.2016
0.037	2.143	5.241	3.899	4.706	0.881	25.Dez.2015
0.809	5.143	4.774	2.721	2.116	0.746	01.Jan.2016
1.833	1.143	9.153	10.526	7.403	3.398	08.Jan.2016
0.43	5.5	6.184	3.124	3.786	0.886	01.Jan.2016
0.79	96.167	4.779	2.344	7.679	1.483	25.Dez.2015

Figure D.7.: Raw data (part 2) of sleep parameters

Row ID	Username	Observation-ID	Profile	Time of Observation	Weight
Row1_dup_d...	Subject 01	4982	MDC_MASS_BODY_ACTUAL	18.Dez.2015	79.7
Row8_dup_d...	Subject 01	10045	MDC_MASS_BODY_ACTUAL	23.Dez.2015	78
Row29_dup_...	Subject 01	20943	MDC_MASS_BODY_ACTUAL	31.Dez.2015	79.5
Row35_dup_...	Subject 01	31870	MDC_MASS_BODY_ACTUAL	06.Jan.2016	78.5
Row42_dup_...	Subject 01	52920	MDC_MASS_BODY_ACTUAL	15.Jan.2016	78.4
Row0_dup_d...	Subject 03	843	MDC_MASS_BODY_ACTUAL	17.Dez.2015	73
Row4_dup_d...	Subject 03	8960	MDC_MASS_BODY_ACTUAL	22.Dez.2015	71.4
Row13_dup_...	Subject 03	10120	MDC_MASS_BODY_ACTUAL	23.Dez.2015	71.5
Row16_dup_...	Subject 03	11325	MDC_MASS_BODY_ACTUAL	24.Dez.2015	70.6
Row17_dup_...	Subject 03	12455	MDC_MASS_BODY_ACTUAL	25.Dez.2015	73.1
Row22_dup_...	Subject 03	16160	MDC_MASS_BODY_ACTUAL	28.Dez.2015	71.4
Row23_dup_...	Subject 03	17651	MDC_MASS_BODY_ACTUAL	29.Dez.2015	71.3
Row27_dup_...	Subject 03	19161	MDC_MASS_BODY_ACTUAL	30.Dez.2015	71.4
Row30_dup_...	Subject 03	22667	MDC_MASS_BODY_ACTUAL	01.Jan.2016	71.1
Row31_dup_...	Subject 03	24374	MDC_MASS_BODY_ACTUAL	02.Jan.2016	72.4
Row36_dup_...	Subject 03	31873	MDC_MASS_BODY_ACTUAL	06.Jan.2016	72.3
Row37_dup_...	Subject 03	42831	MDC_MASS_BODY_ACTUAL	11.Jan.2016	73.4
Row40_dup_...	Subject 03	52760	MDC_MASS_BODY_ACTUAL	14.Jan.2016	71.6
Row6_dup_d...	Subject 04	10018	MDC_MASS_BODY_ACTUAL	23.Dez.2015	59
Row32_dup_...	Subject 04	27786	MDC_MASS_BODY_ACTUAL	03.Jan.2016	58
Row2_dup_d...	Subject 05	5046	MDC_MASS_BODY_ACTUAL	19.Dez.2015	90
Row3_dup_d...	Subject 05	7904	MDC_MASS_BODY_ACTUAL	21.Dez.2015	90
Row19_dup_...	Subject 05	13635	MDC_MASS_BODY_ACTUAL	26.Dez.2015	91
Row20_dup_...	Subject 05	13638	MDC_MASS_BODY_ACTUAL	26.Dez.2015	91
Row5_dup_d...	Subject 06	8970	MDC_MASS_BODY_ACTUAL	22.Dez.2015	89.2
Row7_dup_d...	Subject 06	10039	MDC_MASS_BODY_ACTUAL	23.Dez.2015	89.3
Row9_dup_d...	Subject 06	10060	MDC_MASS_BODY_ACTUAL	23.Dez.2015	89.1
Row10_dup_...	Subject 06	10063	MDC_MASS_BODY_ACTUAL	23.Dez.2015	89.2
Row12_dup_...	Subject 06	10075	MDC_MASS_BODY_ACTUAL	23.Dez.2015	89.2
Row15_dup_...	Subject 06	11304	MDC_MASS_BODY_ACTUAL	24.Dez.2015	89.2
Row18_dup_...	Subject 06	12465	MDC_MASS_BODY_ACTUAL	25.Dez.2015	89.3
Row21_dup_...	Subject 06	13666	MDC_MASS_BODY_ACTUAL	26.Dez.2015	78.5
Row41_dup_...	Subject 06	52911	MDC_MASS_BODY_ACTUAL	15.Jan.2016	90.5
Row14_dup_...	Subject 07	11183	MDC_MASS_BODY_ACTUAL	23.Dez.2015	64.5
Row28_dup_...	Subject 07	20783	MDC_MASS_BODY_ACTUAL	30.Dez.2015	64.3
Row34_dup_...	Subject 07	31861	MDC_MASS_BODY_ACTUAL	06.Jan.2016	64.2
Row38_dup_...	Subject 07	47652	MDC_MASS_BODY_ACTUAL	13.Jan.2016	64.4
Row43_dup_...	Subject 07	60823	MDC_MASS_BODY_ACTUAL	18.Jan.2016	64.2
Row24_dup_...	Subject 08	19046	MDC_MASS_BODY_ACTUAL	23.Dez.2015	78
Row25_dup_...	Subject 08	19060	MDC_MASS_BODY_ACTUAL	23.Dez.2015	78
Row26_dup_...	Subject 08	19119	MDC_MASS_BODY_ACTUAL	25.Dez.2015	79.7
Row33_dup_...	Subject 08	27806	MDC_MASS_BODY_ACTUAL	03.Jan.2016	79.8
Row39_dup_...	Subject 08	47684	MDC_MASS_BODY_ACTUAL	13.Jan.2016	79.5
Row44_dup_...	Subject 08	63592	MDC_MASS_BODY_ACTUAL	19.Jan.2016	79.7
Row45_dup_...	Subject 09	66679	MDC_MASS_BODY_ACTUAL	20.Jan.2016	94

Figure D.8.: Raw data of weight

Row ID	Username	Observation-ID	Profile	Time of Observation	dia. Blood Pressure	sys. Blood Pressure
Row0_dup_d...	Subject 01	8877	MDC_PRESS_BLD_NONINV_DIA	21.Dez.2015	73	?
Row2_dup_d...	Subject 01	8877	MDC_PRESS_BLD_NONINV_SYS	21.Dez.2015	?	129
Row16_dup_...	Subject 01	10048	MDC_PRESS_BLD_NONINV_DIA	23.Dez.2015	78	?
Row20_dup_...	Subject 01	10054	MDC_PRESS_BLD_NONINV_DIA	23.Dez.2015	94	?
Row18_dup_...	Subject 01	10048	MDC_PRESS_BLD_NONINV_SYS	23.Dez.2015	?	125
Row22_dup_...	Subject 01	10054	MDC_PRESS_BLD_NONINV_SYS	23.Dez.2015	?	146
Row52_dup_...	Subject 01	20946	MDC_PRESS_BLD_NONINV_DIA	31.Dez.2015	80	?
Row53_dup_...	Subject 01	20946	MDC_PRESS_BLD_NONINV_SYS	31.Dez.2015	?	130
Row63_dup_...	Subject 01	29849	MDC_PRESS_BLD_NONINV_DIA	05.Jan.2016	70	?
Row65_dup_...	Subject 01	29849	MDC_PRESS_BLD_NONINV_SYS	05.Jan.2016	?	116
Row92_dup_...	Subject 01	50298	MDC_PRESS_BLD_NONINV_DIA	14.Jan.2016	72	?
Row93_dup_...	Subject 01	50298	MDC_PRESS_BLD_NONINV_SYS	14.Jan.2016	?	134
Row37_dup_...	Subject 02	17600	MDC_PRESS_BLD_NONINV_DIA	29.Dez.2015	70	?
Row38_dup_...	Subject 02	17600	MDC_PRESS_BLD_NONINV_SYS	29.Dez.2015	?	110
Row58_dup_...	Subject 02	24377	MDC_PRESS_BLD_NONINV_DIA	02.Jan.2016	72	?
Row59_dup_...	Subject 02	24377	MDC_PRESS_BLD_NONINV_SYS	02.Jan.2016	?	105
Row4_dup_d...	Subject 03	8883	MDC_PRESS_BLD_NONINV_DIA	21.Dez.2015	68	?
Row6_dup_d...	Subject 03	8883	MDC_PRESS_BLD_NONINV_SYS	21.Dez.2015	?	126
Row31_dup_...	Subject 03	11328	MDC_PRESS_BLD_NONINV_DIA	24.Dez.2015	60	?
Row32_dup_...	Subject 03	11328	MDC_PRESS_BLD_NONINV_SYS	24.Dez.2015	?	112
Row34_dup_...	Subject 03	16163	MDC_PRESS_BLD_NONINV_DIA	28.Dez.2015	76	?
Row35_dup_...	Subject 03	16163	MDC_PRESS_BLD_NONINV_SYS	28.Dez.2015	?	104
Row40_dup_...	Subject 03	17666	MDC_PRESS_BLD_NONINV_DIA	29.Dez.2015	85	?
Row41_dup_...	Subject 03	17666	MDC_PRESS_BLD_NONINV_SYS	29.Dez.2015	?	133
Row46_dup_...	Subject 03	19156	MDC_PRESS_BLD_NONINV_DIA	30.Dez.2015	68	?
Row47_dup_...	Subject 03	19156	MDC_PRESS_BLD_NONINV_SYS	30.Dez.2015	?	131
Row55_dup_...	Subject 03	22670	MDC_PRESS_BLD_NONINV_DIA	01.Jan.2016	64	?
Row56_dup_...	Subject 03	22670	MDC_PRESS_BLD_NONINV_SYS	01.Jan.2016	?	124
Row70_dup_...	Subject 03	29929	MDC_PRESS_BLD_NONINV_DIA	05.Jan.2016	78	?
Row72_dup_...	Subject 03	29929	MDC_PRESS_BLD_NONINV_SYS	05.Jan.2016	?	101
Row77_dup_...	Subject 03	31876	MDC_PRESS_BLD_NONINV_DIA	06.Jan.2016	73	?
Row79_dup_...	Subject 03	31876	MDC_PRESS_BLD_NONINV_SYS	06.Jan.2016	?	113
Row81_dup_...	Subject 03	42834	MDC_PRESS_BLD_NONINV_DIA	11.Jan.2016	74	?
Row83_dup_...	Subject 03	42834	MDC_PRESS_BLD_NONINV_SYS	11.Jan.2016	?	116
Row94_dup_...	Subject 03	52754	MDC_PRESS_BLD_NONINV_DIA	14.Jan.2016	72	?
Row96_dup_...	Subject 03	52754	MDC_PRESS_BLD_NONINV_SYS	14.Jan.2016	?	127
Row68_dup_...	Subject 04	29878	MDC_PRESS_BLD_NONINV_DIA	05.Jan.2016	74	?
Row69_dup_...	Subject 04	29878	MDC_PRESS_BLD_NONINV_SYS	05.Jan.2016	?	101
Row8_dup_d...	Subject 06	8964	MDC_PRESS_BLD_NONINV_DIA	22.Dez.2015	72	?
Row10_dup_...	Subject 06	8964	MDC_PRESS_BLD_NONINV_SYS	22.Dez.2015	?	114
Row12_dup_...	Subject 06	10033	MDC_PRESS_BLD_NONINV_DIA	23.Dez.2015	72	?
Row25_dup_...	Subject 06	10066	MDC_PRESS_BLD_NONINV_DIA	23.Dez.2015	70	?
Row14_dup_...	Subject 06	10033	MDC_PRESS_BLD_NONINV_SYS	23.Dez.2015	?	123
Row26_dup_...	Subject 06	10066	MDC_PRESS_BLD_NONINV_SYS	23.Dez.2015	?	120
Row98_dup_...	Subject 06	52914	MDC_PRESS_BLD_NONINV_DIA	15.Jan.2016	66	?
Row100_dup...	Subject 06	52914	MDC_PRESS_BLD_NONINV_SYS	15.Jan.2016	?	111
Row28_dup_...	Subject 07	11178	MDC_PRESS_BLD_NONINV_DIA	23.Dez.2015	70	?
Row29_dup_...	Subject 07	11178	MDC_PRESS_BLD_NONINV_SYS	23.Dez.2015	?	111

Figure D.9.: Raw data (part 1) of blood pressure

Row ID	Username	Observation-ID	Profile	Time of Observation	dia. Blood Pressure	sys. Blood Pressure
Row29_dup_...	Subject 07	11178	MDC_PRESS_BLD_NONINV_SYS	23.Dez.2015	?	111
Row49_dup_...	Subject 07	20786	MDC_PRESS_BLD_NONINV_DIA	30.Dez.2015	71	?
Row50_dup_...	Subject 07	20786	MDC_PRESS_BLD_NONINV_SYS	30.Dez.2015	?	109
Row75_dup_...	Subject 07	31856	MDC_PRESS_BLD_NONINV_DIA	06.Jan.2016	72	?
Row76_dup_...	Subject 07	31856	MDC_PRESS_BLD_NONINV_SYS	06.Jan.2016	?	110
Row86_dup_...	Subject 07	47655	MDC_PRESS_BLD_NONINV_DIA	13.Jan.2016	69	?
Row87_dup_...	Subject 07	47655	MDC_PRESS_BLD_NONINV_SYS	13.Jan.2016	?	108
Row103_dup...	Subject 07	60826	MDC_PRESS_BLD_NONINV_DIA	18.Jan.2016	72	?
Row104_dup...	Subject 07	60826	MDC_PRESS_BLD_NONINV_SYS	18.Jan.2016	?	110
Row43_dup_...	Subject 08	19122	MDC_PRESS_BLD_NONINV_DIA	25.Dez.2015	66	?
Row44_dup_...	Subject 08	19122	MDC_PRESS_BLD_NONINV_SYS	25.Dez.2015	?	121
Row61_dup_...	Subject 08	27809	MDC_PRESS_BLD_NONINV_DIA	03.Jan.2016	63	?
Row62_dup_...	Subject 08	27809	MDC_PRESS_BLD_NONINV_SYS	03.Jan.2016	?	118
Row89_dup_...	Subject 08	47679	MDC_PRESS_BLD_NONINV_DIA	13.Jan.2016	82	?
Row90_dup_...	Subject 08	47679	MDC_PRESS_BLD_NONINV_SYS	13.Jan.2016	?	124
Row106_dup...	Subject 08	63595	MDC_PRESS_BLD_NONINV_DIA	19.Jan.2016	75	?
Row107_dup...	Subject 08	63595	MDC_PRESS_BLD_NONINV_SYS	19.Jan.2016	?	118
Row109_dup...	Subject 09	66674	MDC_PRESS_BLD_NONINV_DIA	20.Jan.2016	119	?
Row110_dup...	Subject 09	66674	MDC_PRESS_BLD_NONINV_SYS	20.Jan.2016	?	169

Figure D.10.: Raw data of (part 2) of blood pressure