Smart medical textiles for monitoring patients with heart conditions

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November 2006

1 Introduction

Cardio-vascular diseases (CVDs) are a prevalent type of chronic diseases with epidemic mortality rates. CVDs are a main cause of life years lost from early death in developed countries. The CVD group includes high blood pressure, coronary heart disease, heart failure and stroke. The most prominent risk factors include diet, physical activity, hypertension and blood cholesterol, overweight and obesity, diabetes and stress. Each individual risk factor increases the probability for a CVD when left untreated for several life years at a critical state. However persons with a high score in the risks already suffer from a decreased quality of life. E.g. obese persons encounter severe limitations in their ability to follow an active lifestyle. Moreover, after a cardio-vascular event patients suffer from strong reduction in quality of life. A majority of patients are afraid to take an active role in their life and potentially develop a depression.

In Europe ∼49% of all deaths are attributed to CVDs and more than 23% of all European citizens suffer from a chronic CVD (Petersen et al., 2005). Recent numbers for the US are similar[1]: Thom et al. (2006) reports a a mortality rate of 58% for CVD as underlying or contributing cause and a disease prevalence of 34%. One growing cause of the CVD prevalence is the increasing life expectancy (ESC, 2004). With it the disease management cost raises. Currently CVDs are estimated to cost the EU economy 169 billion Euros per year, including 105 billion direct health care costs (professionals, hospital and nursing home services). However these numbers underestimate indirect costs (lost productivity, informal care) (Petersen et al., 2005). The economic cost associated with CVDs in the US is estimated to 403 billion

[1] Statistics based on preliminary data for the years 2002-03.

USD[2], including direct costs and indirect cost (Thom et al., 2006). These numbers indicate that it will become increasingly challenging for communities to provide its citizens with the best health care service at affordable costs.

1.1 Preventive lifestyle and early diagnosis

The major CVD risk factors presented above indicate, that individual lifestyle is an important disease indication. The cardiology community [3] has developed lifestyle and diet recommendations to effectively prevent CVD, identify risks and optimise post-event treatment outcomes, e.g. (Lichtenstein et al., 2006; Kelly and Stanner, 2003; Wood and EUROASPIRE I and II Group, 2001; Bauman, 2004).

A healthy and preventive lifestyle (primary prevention) and early diagnosis as well as optimised post-event support (secondary prevention) could save millions of life years and improve quality of life for patients. Primary and secondary prevention reduce individual risk factor scores and effectively prevent recurring of cardio-vascular events. In this way prevention can fight the origin of CVD systematicly and is believed to become the solution for improving the quality of care in the future.

Prevention aiming at a healthy lifestyle is a continuous lifelong challenge for individuals. It cannot be thoroughly provided by the current medical service centres, e.g. hospitals and office-based physicians. This classic institutional point of care approach offers intermittent treatment only, focused on brief and expensive supervised episodes. However prevention requires a continuous health care delivery emphasising a long-term change of habits. Due to the inherent cost structure institutional care cannot achieve a cost-effective level for continuous treatment and prevention. Novel methods are needed to provide continuous and ubiquitous access to medical excellence in a cost-effective way.

The challenge of prevention stems furthermore from the difficulty of individuals to adapt to it. Knowing risks and preventive measures does not automatically lead to a successful adoption by individuals however. Wood and EUROASPIRE I and II Group (2001) indicated that even in a high-risk group the adoption of secondary prevention is rather limited. Success achieved in clinical settings could not be continued after patient discharge. Thus appropriate motivation concepts are needed to bridge the prevention gap.

In order to empower individuals to adopt prevention as a lifestyle the following challenges were identified (Schmidt and Lauter, 2005): 1) the scientific challenge to find solutions for prevention and early diagnosis, 2) the

[2] Cost statistics for 2006.

[3] European Hearts Network: http://www.ehnheart.org, British Heart Foundation: www.bhf.org.uk, American Heart Association: http://www.americanheart.org

technical challenge to develop solutions that allow ubiquitous access to medical expertise for empowering the individual to adapt a healthy life style and early diagnosing of acute events, and 3) the psychological challenge to create pleasant and easy to use solutions that motivate people to adapt lifestyle and improve their quality of life. The MyHeart project was initiated by Philips as an integrated project, including research and development of solutions, with the objective to address all three challenges.

1.2 Solutions for prevention and early diagnosis

To accommodate the needs of individuals a segmentation of application areas and user groups was developed. The segmentation contains five application clusters and four customer groups and was chosen to simplify the design of solutions tailored to specific user groups and motivational needs. The customer groups cover 1) individuals who want to stay healthy, 2) individuals with recognised risks for developing CVDs, 3) individuals after a cardiac event and 4) chronically ill patients (Lauter, 2004).

The application clusters reflect main risk groups for developing CVD and address the user's need for early diagnosing to limit severity of an acute event. The following segmentation was presented before by Schmidt and Lauter (2005) and is summarised in updated form here.

CardioActive: Application cluster for improved physical activity Sedentary lifestyle is a major risk factor for developing CVD and physical activity is widely known to decrease various CVD risks, e.g. (Bauman, 2004; Petersen et al., 2005; Cress et al., 2006). People must be made aware of this, and stimulated to be more active. For this group solutions are developed to determine the activity levels and include assessment of fitness condition of the user. The solutions include the sensing of basic vital signs like heart rate, breathing rate and activity classification as well as the determination of speed, distance and height levels. The system automatically determines the specific activity and gives feedback on the present status as well as on the achieved improvement of the physical status. Specific training plans and recommendations for training will be personalised on the individual condition and the ambition level of the user. Specific attention is paid to the motivation for staying active by feedback on status, community building and virtual competition.

CardioBalance: Application cluster for improved nutrition and dieting Diet is an important health aspect and obesity the most prominent form of malnutrition. For these individuals solutions are developed to actively manage their dieting and nutrition by personalised dieting plans, continuous feedback, guided physical training plans. Special attention is paid to the motivation of the customer via community building and new methods of electronic peer pressure.

CardioSleep: Application cluster for improved sleep and relaxation phases Sleep quality and disorders as sleep apnoea and insomnia are relevant risk areas for CVD, e.g. (Coccagna et al., 2006). Patients are at elevated risk to develop a CVD. Solutions are developed to assess the individual's sleep quality and diagnose sleep disorders at home. Novel methods for improving sleep quality and the therapy of sleep disorder based on biofeedback and personalised relaxation exercises are explored. Special attention is paid to diagnosing sleep quality related diseases like depression, which is a frequent complication of post myocardial infarction patients.

CardioRelax: Application cluster for improved solutions to deal with stress Stress is a major behavioural risk factor for CVD. Solutions are developed not only for diagnosing acute stress situations and a stress meter but also for specific relaxation methods to deal with stress. Biofeedback tools are used tailored to individual needs and enabled by Web and mobile services. The solution will limit the stress related risk for CVD and will improve the personal performance in the working environment.

CardioSafe: Application cluster for early diagnosis and prediction of acute events For the early diagnosis solutions are developed to continuously analyse the vital signs of the individual in order to determine and predict acute events. A diagnosis system for the following areas is developed: 1) myocardial infarction, 2) stroke prevention, 3) pump failure prevention, 4) sudden cardiac arrest prevention and 5) hypo-hyperglycemic shock.

1.3 MyHeart applications

In order to tailor solutions within the application-customer segmentation scheme the notation of concepts was defined. A concept is an application solution that addresses a specific application cluster and customer group. In the first project phase individual concepts were developed and evaluated according to different criteria, including 1) application value proposition, 2) technical feasibility and 3) stakeholder opinion and acceptance, e.g. potential users and service providers.

At the end of the first project phase a selection and combination of individual concepts was performed and new product concepts (PCs) were established. The PCs represent combinations of concepts for specific customer groups addressing multiple application clusters. Fig. 1 visualises the segmentation and concept approach.

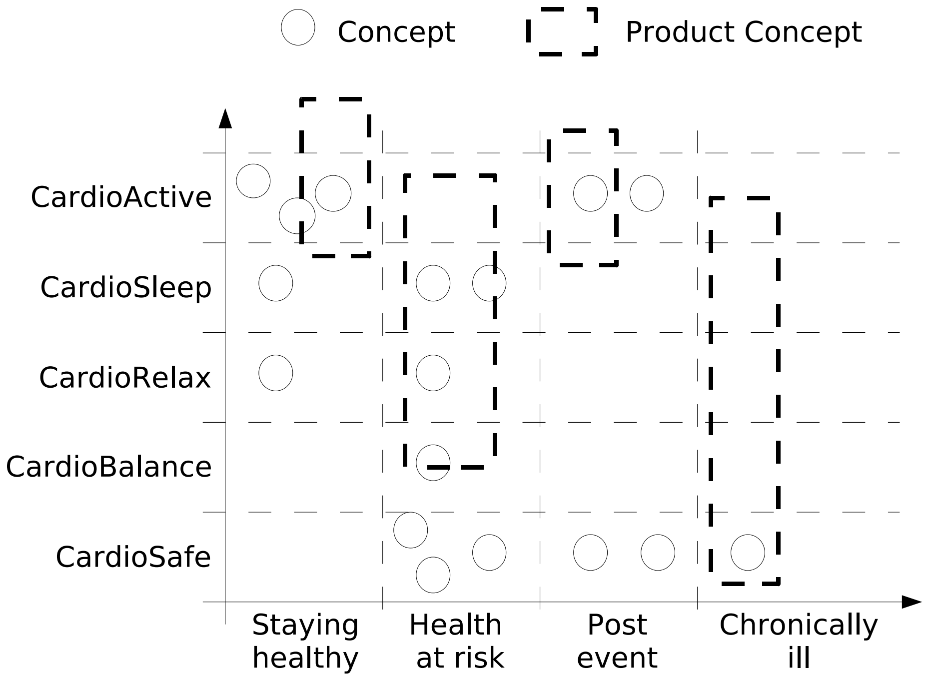

Figure 1: Segmentation of applications and customer groups as applied in the MyHeart concepts. The concepts (addressing individual application cluster and customer group) and Product Concepts (PCs) are shown. Adapted from Schmidt and Lauter (2005).

1.4 MyHeart organisation

The MyHeart project is a joint effort of the European Commission and 33 partners from industry and academics. A partitioning in work packages and project phases is applied to structure both applications and development cycles. The project schedule is segmented into phase 1) development and evaluation of application concepts, phase 2) development of product concepts to prototypes of commercial solutions and 3) product concept validation. A detailed description of the project organisation is provided by Lauter (2004). The project was started in January 2004 and is scheduled to be finalised by September 2007. Currently the project is in the product concept validation. However research into novel solutions is continued and results will be integrated into the applications under evaluation when appropriate.

2 Personal health care: from monitoring to coaching

MyHeart aims at fighting CVD by preventive lifestyle and early diagnosis. In order to achieve this target, innovative easy-to-use solutions and tools are required. These solutions must integrate the sensing of relevant health parameters to provide the ground for a health status estimation. Only based on the estimated current status appropriate recommendations using personal profiles can be provided. Hence it is needed to continuously acquire sensor information and analyse the health status. The remainder of this section presents the technical objectives and briefly describes the MyHeart concepts (applications).

2.1 Technical objectives

For the continuous measurement of vital signs electronic systems and sensors are developed embedded into functional cloths. Sensors are partly based on textile materials. The garments are able to monitor vital signs continuously and analyse the data. Furthermore the cloths feature a wireless transmission link to transfer the acquired and processed information to user feedback devices and - if necessary - to professional medical services. The automatic processing involves status diagnosis, trend estimation and system reactions (therapy recommendations). Additional services are available through the link to professional care suppliers.

Fig. 2 visualises the different technical objectives of MyHeart. These objectives have been presented by Schmidt and Lauter (2005) and are summarised here.

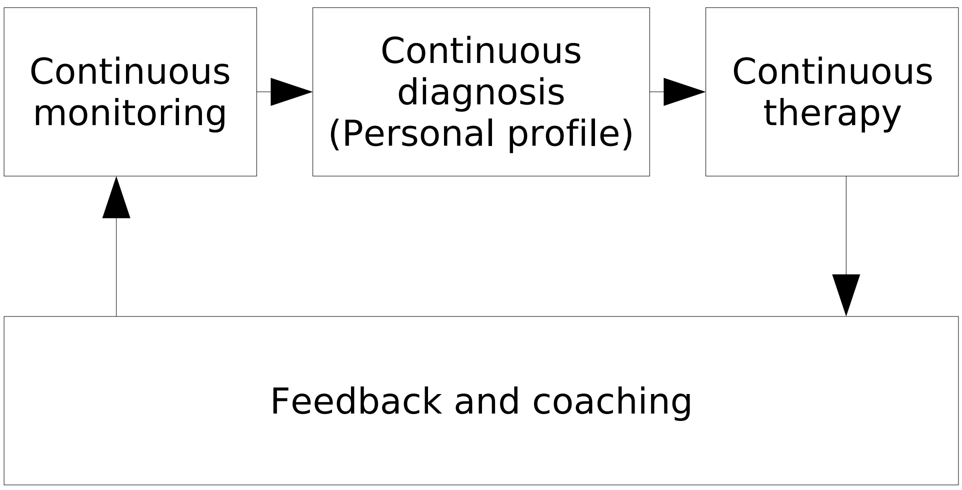

Figure 2: Monitoring, analysis/diagnosis, feedback cycle applied in the MyHeart project. Adapted from Lauter (2004).

Continuous monitoring The first basic requirement of preventive lifestyle and early diagnosis of acute events is a continuous monitoring of the cardiovascular system. This challenge is addressed by the integration of novel sensors and monitoring systems into functional clothes. A basic set of clothes are investigated and developed that allow the continuous monitoring throughout the day. Only three garments will serve the full spectrum of prevention: 1) garment for the night (@night: night-dress, pyjama), 2) garment for the day (@day: functional undergarment), and 3) garment for sports (@sports: functional fitness dress). With this approach, a coverage of nearly 100% of a user's life is achieved.

Continuous personalised diagnosis The intelligent biomedical clothes provide a modular basis for the pioneering of an on-body diagnosis system that allows the continuous assessment of health status and analysis in a wearable on-body system. The personal sensor signals are analysed and high-quality diagnosis of the health status is enabled. One major challenge is the development of these personalised diagnostic and trend detecting algorithms and the technology to operate the analysis algorithms in wearable electronics. By combining clinical protocols and clinical knowledge with continuous on-body diagnose systems access to clinical excellence is provided on a life-long timescale and in a continuous way.

Continuous therapy The intelligent biomedical clothes provide detailed and precise information on the actual health condition. Therapy is provided in form of specific user instructions and information. Examples are on-line recommendations during sports to adapt heart rate and breathing rate. The dynamic posture and gesture recognition allows home training and physical therapy in the home setting under supervision of trainers. Furthermore the recognition supports behavioural algorithms for lifestyle analysis. Biofeedback technologies are developed for stress and relaxation exercises. Personal treatment recommendations and feedback on the success of activities represent a tool to motivate the user continuing their preventive lifestyle. Opportunities for novel self-medication approaches are explored for the acute medical part, e.g. pill-in-the-pocket.

Feedback to user User terminals are adapted that allow the visualisation of recommendations and biofeedback in the home and in the mobile setting, anytime and anywhere. Mostly existing platforms and infrastructure, e.g. GSM and UMTS networks in the mobile setting are utilised as well as existing home infrastructure like TV, personal computers and audio-systems. Health status, instructions for adapting the lifestyle and notifications of preventive actions are displayed automatically on mobile terminals and connected home devices. Concepts are developed for a health aware home with special emphasis on ease-of-use aspects.

Remote access and professional interaction Innovative communication systems connect the user to professional medical services and to other users in the home and mobile setting. Architectures and concepts for direct and immediate access to institutional care at anytime are explored. There is a need for application specific modules that enable professionals the interaction with MyHeart applications. Moreover, tools for the management of the MyHeart system from external site as well as interfaces of the MyHeart platform with general and third party resources have to be developed. The systems allow the interaction with professional service providers and public emergency systems.

2.2 MyHeart concepts and Product Concepts (PC)

As presented in the introduction, MyHeart addresses various different application clusters and customer groups by implementing different concepts. In the first project phase 16 concepts were developed and evaluated where each focused on an individual application cluster and one or two user groups. Tab. 1 lists the different evaluated concepts and indicates responsible partners. These partners may be contacted for further information regarding the specific concept.

The second phase established four product concepts (PCs) to drive the development further and approach product solutions. The PCs are summarised in Tab. 2. These PCs are further developed in the current project phase. Main technical challenges originating from these applications are discussed in Section 3.

Table 1: MyHeart concepts in the first project phase.

Concept	**Description and corresponding partner**
Virtual trainer	Assess physical performance and assist with personalised training plans for different sports and ambition levels, ITACA, E.
Prevention Manager	Guide and motivate runners with adaptive music to sport at a pace that is most effective for your health, Philips Research Labs, NL.
Outdoor rehabilitation	Solutions for different outdoor activities (e.g. biking, walking) tailored and personalised for rehabilitation needs of CVD patients, Dr. Hein GmbH, D.
Interactive exercises	Interactive exercises using vital signs and body motion for feedback and input, Consorzio di Bioingegneria e Infomatica Medica, I.
Stroke rehabilitation	Interactive stroke rehabilitation program to improve motor control physical performance, University of Pisa, I.
Sleep disorders	Assessment of sleep quality, early diagnosis of sleep disorders and improvement of sleep quality, Politecnico di Milano, I.
Depression Management	Early diagnosis of recurrence of depression on the basis of sleep fragmentation, Philips Research Labs, D.
Cardio Relax 1	Stress relaxation based on biofeedback (HRV, breathing) and audio-visual experiences, Mind Media BV, NL.
Cardio Relax 2	Continuous stress meter and personalised mental balance indicator, Mind Media BV, NL.
Obesity management	Concept providing obese adolescents with monitoring services and tools that help them to lose weight, reduce their cardiovascular risk, reintegrate into a social network and rebuild confidence, Medgate AG, CH.
Sleep & Care	Early detection of decompensation of CHF patients by daily measurements during sleep with bed based sensors, Philips Research Labs, D.
MI prevention	Early detection of ischemic events based on haemodynamic indicators (myocardial infarction, MI), Philips Research Labs, D.
Stroke prevention	Prevention of atrial fibrillation (AF) induced strokes by early detection and treatment of AF episodes, Philips Research Labs, D.
My HF-web Risk Monitor	Detect early indicators for heart failure (HF) and if necessary direct the user to institutional points of care for further treatment, Medtronic SA, E.
Hypoglycemic shock prevention	The continuous measurement of ECG, breathing rate and activity will be used to develop solutions to detect and potentially also predict hypoglycemic events, University of Padova, I.
Post Intervention Follow Up	Early detection of evolving life-threatening risks associated with 1) prosthetic heart valve dysfunction and 2) Sudden Cardiac Death due to ventricular arrhythmia, University of Coimbra, P.

Table 2: MyHeart concepts in the second project phase.

Product Concept	**Description**	**Corresponding partner**
Activity Coach	Supports and motivate users in reaching and maintaining personal training goals.	University of Madrid, E
Take Care	Screening tool for consumers which gives feedback and coaching to (self)-manage CVD risk factors and adapt a healthier lifestyle.	Philips Research Labs, Aachen, D
Neurological rehabilitation	Support patients and their caregivers during neurological rehabilitation exercises, of both cognitive and physical type.	Dr. Hein GmbH, D
Heart Failure Management	Early detection of decompensation of heart failure patients based on automated vital body signs trend analysis and arrhythmia detection at the patients home.	Philips Research Labs, Aachen, D

3 Technical challenges for monitoring, analysis and feedback

This section provides an overview on the MyHeart application challenges from a technology viewpoint. After reviewing the overall technical approach and information flow, individual problems of sensor data acquisition in garments, on-body signal analysis and transmission as well as user feedback are discussed. Emphasis is set on garment based solutions and primarily used sensors. References to further research works are provided were appropriate. The section is concluded by summarising the lessons learnt of wearable system design and integration.

3.1 Methodology

The different MyHeart applications require the integration of monitoring, analysis (mostly signal processing) and feedback facilities. A generalisation of the data flow is visualised in Fig. 3. While concepts share some modules not all concepts require the identical type and number of sensors, feature analysis and feedback functions.

For the monitoring task mainly wearable on-body sensors are used. This design choice is essential to achieve the project goal of continuous everyday physiologic monitoring. The sensors provide the main input for the analysis

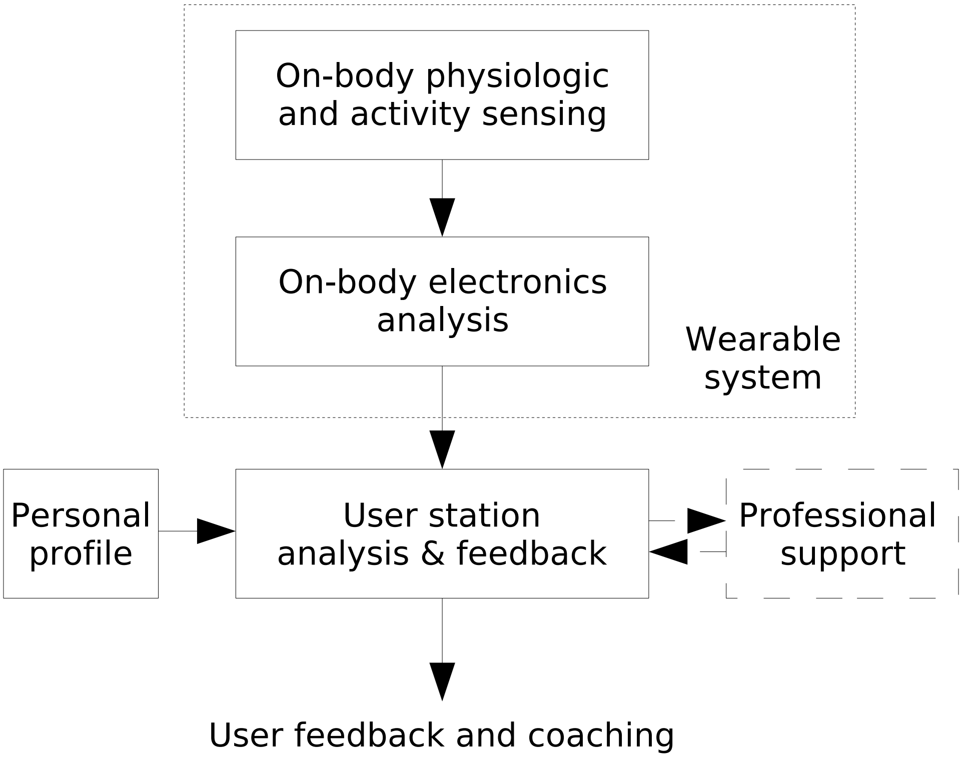

Figure 3: Generalised data and information flow as applied in the MyHeart concepts.

step. Manual input of data is avoided as far as possible to minimise the user's burden and measurement errors. However, for some concepts an additional instrumentation of the environment is integrated to support the analysis step, e.g. for the PC Activity Coach information from a gym bicycle or step device is integrated to support user performance estimation. Environmental sensing support is not discussed in this work however.

The analysis task refers to signal data acquisition, filtering and signal processing functions. The signal processing aims at deriving features as well as behavioural pattern classifications and trend estimations that can be used in feedback procedures. The wearable system is formed by the on-body monitoring and signal processing tasks.

Finally, the feedback and coaching task provides appropriate indications to the user. This is achieved by a combination of 1) presenting analysis results directly at the user station, 2) using automated recommendation messages based on analysis results and 3) manual or semi-automated filtering of analysis results by a professional health care centre.

From the tasks described above the following basic requirements were derived: 1) the wearable solution must solve the given application robustly with a high reliability in everyday life situations, 2) wearable system components worn close to the skin must be cleanable, 3) the system must be easy to operate and control for non-trained users and finally 4) a minimal hindrance for normal activities of the user shall be imposed from both the wearable devices and the required system interactions.

The challenges for the on-body monitoring task can be summarised as 1) finding appropriate physiologic and activity signals and sensing locations, 2) developing appropriate sensors and integrating the sensors into a wearable system, e.g. a T-shirt or chest band and 3) extracting relevant features from the raw sensor data. The implementation and achieved results for the monitoring task within the MyHeart project are further detailed in Section 3.2.

Since the project focuses on wearable sensing solutions much work is targeted at preprocessing the sensor signals on the body. Hence the challenges of the analysis task can be summarised to 1) designing small and energy-efficient electronics that can process the sensor data, 2) developing an interconnection solution between electronics and the garment sensors and 3) adapting the signal processing algorithms to run on the constrained hardware. The implemented solutions are further discussed in Section 3.3.

Finally the means for feedback and the coaching concept must be developed. This includes coaching and behavioural analysis algorithms of elevated processing effort that are not provided by the on-body electronics, visualisation of analysis results and strategies to motivate the user. The feedback devices deployed for the project are discussed in Section 3.4. The psychological theory and the applied strategies are beyond the scope of this chapter however.

3.2 Physiology and activity monitoring and feature extraction

The MyHeart concepts mainly require features based on the Electrocardiogram (ECG), respiration and motion activity detection. Different implementation solutions and associated research issues are discussed in this section. Further monitoring approaches that are specifically tied to individual applications are summarised in the section on further research (Section 4).

Electrocardiogram Features continuously derived from heart activity are important information sources for all concepts, e.g. for heart failure detection, energy expenditure and stress management. The integration of different sensing approaches in textiles was tested in the first phase of the MyHeart project, including impedance cardiography, phonocardiography and ECG. The current project phase focuses on the latter and aims at improving the sensing and analysis as described below.

Electric potentials of the heart activity seen as an electric equivalent generator are measured by surface electrodes on the chest. These measurements

Figure 4: Prototypes of the MyHeart shirt and band textiles (courtesy R. Paradiso, Smartex, Italy). Textile electrode positions are indicated, see text.

provides very low voltage amplitudes ($\sim 1mV$ for R-wave) due to the resistance of the thoracic medium and skin contact. Artefacts are introduced from other muscle activity, e.g. due to body movements. A complete cardiograph waveform provides detailed insight into the ventricle functions, e.g. the P, Q, R, S and T waves as well as the various inter-wave-timings. The R-wave is usually counted over time to derive the heart rate (HR) per second. Besides the RR-timing ($HR = 1/RR$), the heart rate variability (HRV) is a relevant health status indication, e.g. for the estimation of stress level.

In continuous monitoring ECG applications alternatives to gel-based (wet) silver/silver-chloride electrodes are sought. Different dry electrode approaches have been proposed and compared (Searle and Kirkup, 2000), however the aimed textile integration is still an open research problem. Two main design approaches have been considered: 1) yarns made of stainless steel slivers blended with viscose textile yarn and 2) conductive rubber thermally moulded on a textile patch. The critical issues include the quality of skin contact, selection of conductive material, yarn processing and the electrode positioning. The problem of electrode positioning applies to gel electrodes as well: artefacts introduced by muscle activations during body movement or exercises must be compensated by positioning of the electrodes. With the use of textile or conductive rubber electrodes this effect is exacerbated due to potentially weaker skin contact and material conductivity. Hence these aspects require special attention in the design of textile solutions. Mühlsteff and Such (2004) reported the development of a conductive rubber electrode. For a 24 hour monitoring using a chest strap device a coverage with acceptable signal quality of ∼70% was achieved (Mühlsteff et al., 2004). Twelve users participated in this study.

Investigations were direct to compare and qualify textile electrode solutions with their gel-based counterparts. Results of these works were presented in (Scilingo et al., 2005; Loriga et al., 2005; Luprano et al., 2006). Fig. 4 shows the sensor layer of a prototype shirt as it is used in MyHeart with position indications for the textile electrodes. The electrodes are realised using stainless steel slivers blended yarn. Fig. 5 shows different time-series plots from a simultaneous measurement using gel and textile electrodes during light physical activity. The signal waveforms correspond to the textile electrode pairs A-I, A-S, E-S and gel electrode pairs R-L, L-F, R-F as labelled at the prototype shirt (cf. Fig. 4). While the gel electrodes still provide a good signal to noise ratio (SNR) in this situation, the textile electrodes knitted into the garment reflect the expected patterns weakly. The SNR is improved by increasing electrode pressure on the skin and hence decreasing friction and movements. However that is achieved primarily by tight fitting of the shirt and consequently a decreased user comfort. One specific problem was observed with the position of electrode E at the centre of the sternum as this location has a weak skin contact depending on body shape.

The current work is aiming at improving signal processing algorithms for the feature extraction and textile sensor data quality in parallel. To ameliorate data quality different materials, embroidery and electrode locations are evaluated. Good initial results were achieved by using hydrophilic membranes (Paradiso et al., 2004). The membrane is reported to decrease contact resistance and improve wearing comfort (Scilingo et al., 2005).

The ECG enhancement and feature extraction is extensively researched. An overview is provided by the following works (Xu et al., 2001; Köhler et al., 2002; Hamilton et al., 2000). Luprano et al. (2006) achieved acceptable results for the R-wave extraction using textile electrodes. They used an algorithm based on the first derivative of the ECG time series supported by thresholds on the second derivative and the ECG signal itself. Additionally the plausibility of the RR interval is tested and unlikely false beat periods are omitted. The enhancement of a complete QRS complex is achieved by replacing the original signal with an adaptive template. The template is adapted continuously from the source data. While this approach achieves a good QRS waveform it drops time variation in the complex and is not suitable for the analysis of heart pathologies.

Respiration Respiration sensing is used in all concepts mainly to support activity and energy expenditure estimation during daytime and apnoea de-

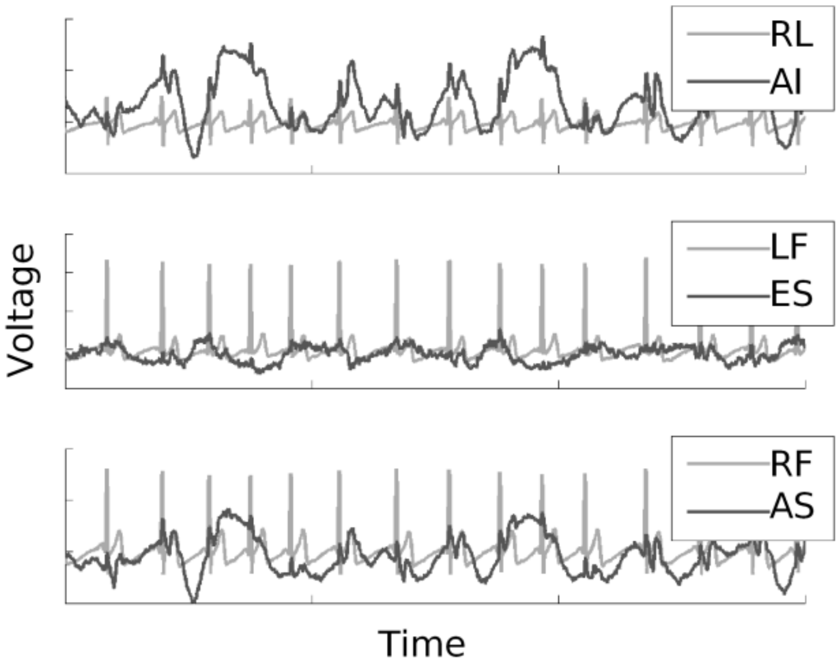

Figure 5: Simultaneous recording of wet and textile electrode ECG during light physical activity. Adapted with permission from Luprano et al. (2006).

tection during sleeping. From the respiration signal the breath rate and variability (tidal volume) are extracted. The respiration wave is derived from the perimeter variation of the trunk due to the cyclic change of thoracic volume when breathing. Several measurement methods for the acquisition of respiration waves at the chest exist: 1) electric impedance pneumography, 2) respiratory inductive plethysmography (RIP) and 3) strain-sensitive chest band(s). These methods differ in the chest circumference detection principle. While the first method requires electrodes for current injection and measurement, the latter two measure the mechanical change of perimeter directly at thoracic and abdominal levels. Especially the RIP method has shown good accuracy in stationary settings (Cohen et al., 1997; McCool and Paek, 1993). The piezoelectric strain-gauge sensors were successfully embedded into a shirt for the IST Wealthy project[4] (Paradiso et al., 2005). Since these sensors permit simple integration into a garment, respiration sensing in MyHeart follows that approach for the Product Concepts. However, the reliability of respiratory information derived with the strain gauge method is limited due to motion artefacts (Primiano, 1998).

[4]http://www.wealthy-ist.com

Physical activity and motion While most concepts require a categorical estimates of user motion activity, for specific applications a detailed detection of user movement is needed, e.g. the PC Neurorehabilitation to estimate the movement quality of user during training or in PC Take Care to support nutrition behaviour inference using the user's gestures.

Categorical levels of motion activity are qualified as no activity to very strong activity in 3 to 5 levels or direct activities, e.g. standing/sitting, walking and lying. Here, the categorical classification is also used to determine whether the user is using/wearing the system.

Common solutions for activity level estimation integrate a two- or three-axis accelerometer (usually based on Micro-Electro-Mechanical Systems, MEMS) attached at the waist level, e.g. (Bouten et al., 1996; Mathie et al., 2004). With the use of a shirt or chest band this position had to be shifted to an unobtrusive location at the chest. To obtain a robust system two implementations were used: 1) to sew the packaged sensor into the garment and 2) to integrate the sensor directly into the on-body electronics. While the latter approach is technically simpler, since it avoids additional data and power transmission lines within the textiles, the first solution may provide more accurate estimation results due to improved location. In the sewed version the sensor electronics are moulded in a waterproof medical silicon material to permit normal washing of the garment. This approach is similar to the direct glob-top encapsulation of electronic packages on textiles (Peek, 2001). Package dimensions below $15\,mm^2$x4 mm were achieved (Luprano et al., 2006). For the automatic classification of activity levels a good fidelity is obtained. Sola et al. (2005) achieved an accuracy of 80% for the discrimination of no activity, walking, using stairs and running with a manually configured decision tree algorithm.

More elaborate movement detection is used in scenarios that require a detailed posture and gesture analysis of the upper body. Within MyHeart posture detection of the upper body is used to estimate the quality of movement (Tognetti et al., 2005; Guilemaud et al., 2004) in the PC Neurorehabilitation. Gestures are investigated to support inference of user behaviour (Amft et al., 2005a) for lifestyle coaching in the PC Take Care. Two technical solutions for the motion monitoring are investigated: 1) usage of inertial sensors and 2) utilisation of sensors based on piezoelectric materials. The first approach can be understood as a generalisation of the activity level detection, since it extends the set of sensors from one three-axis accelerometer to a combination of several acceleration, gyroscope and compass sensors. All of them are available as off-the-shelf components with very low form factor[5]. Since piezoelectric materials respond with an electric voltage

[5] three-axis accelerometer: 7x7x2mm (ST Microelectronics); one-axis gyroscope: 7x7x3mm (Analog Devices ADXRS); three-axis compass: 7x7x2mm (Honeywell HMC).

to mechanical deformation, research was done to deploy this property for the monitoring of limb movement, e.g. (Edmison et al., 2002). Piezoelectric materials are either directly embedded into a yarn and embroidered or woven into a textile or externally attached, e.g. by coating onto a fabric. The latter method is currently investigated in the project for upper limb postures (Lorussi et al., 2005). The merit of this second approach to motion monitoring is its seamless integration into a garment while inertial sensors are robust and established devices in the sensor market, cheaply available in large quantities. Since the processing effort and energy consumption increases with the number of sensors, emphasis must be given to optimise the sensor count for continuous monitoring applications.

For the discrimination of a set of dietary gestures using a Hidden Markov model algorithm and inertial sensors attached to the arms a performance of ∼90% correct detections was achieved (Amft et al., 2005a).

3.3 Signal transmission and on-body electronics

Tab. 3 summarises a typical set of sensors integrated into a MyHeart garment and their corresponding bandwidth requirements. Considering the typical set of sensors (ECG, respiration, acceleration) the sensors require a bandwidth of 5.4 kbps, amounting to ∼445 MiB of data in 24 hours. An on-body processing of these signals is applied to derive relevant features before storing or transmitting the data from the body. Moreover, analog-digital conversion of the sensor signals must be done as close as possible to the sensor to optimise signal quality, transmission lines and bandwidth usage. In the following section selected solutions for interfacing sensors in the textile and on-body processing are discussed.

Table 3: Acquired signals and bandwidth requirements in the garment.

Signal	**Sampling rate**	**Digital Resolution**	**Bandwidth**
Electrocardiogram	250 Hz	12 bit	3 kbps (1 lead)
Respiration	50 Hz	12 bit	0.6 kbps (1 band)
Acceleration	50 Hz	12 bit	1.8 kbps (3 axis)
Total			5.4 kbps

Body sensor network In order to obtain a system simple to operate and control a centralised system architecture was selected. This concept requires that all sensors communicate to a central processing master unit at the shirt. In this way individual sensors and the cleaning process are strongly simplified since individual battery, processing and transmission electronics are avoided. However this is achieved at the expense of individual analog or digital transmission and power lines for each sensor. The main challenges for the sensor attachment are 1) selecting a flexible signal line routing and 2) interfacing the sensor with the signal line appropriately.

Various approaches to establish electrical wiring structures in textiles exist. An overview is provided by Locher (2006). Textile conductivity is achieved by integrating conductive threads during the textile manufacturing process, e.g. by weaving a metal wire with the yarn, or enabled after manufacturing, e.g. by sewing or printing/plating. For the MyHeart sensor network the woven metal wire approach is most feasible. Relevant research results are available that characterise the electrical transmission properties for this approach, e.g. (Locher, 2006; Cottet et al., 2003; Dhawan, 2004).

Fig. 4 introduced the sensor (skin) layer of a prototype shirt as it is used in the project. For this initial garment a solution based on the second approach was chosen to simplify reconfiguration: transmission and power lines were sewn in "cable ducts" along textile patches. This approach, however, required to include provisions for textile stretching across the body since the conductive lines cannot be elasticly elongated. Ducts and spare cable is finally covered by a top layer textile (not show in Fig. 4). Wire attachments were either embroidered for the textile electrodes or included in the mould for the acceleration sensors.

On-body electronics As shown in Fig. 3 above, the on-body processing must acquire, filter and process sensor data as well as store and forward processing results wirelessly to the user station. On-body result storage is needed for concepts that use a stationary user feedback system, e.g. placed or integrated in the user's home. In these concepts the on-body electronics must transfer the data at certain times, e.g. in the evening when the user is at home and the station is in wireless communication reach. The communication with the user station is realised by a Bluetooth connection. Critical system aspects include computational performance and power requirements as well as system size and provisions for garment cleaning.

As introduced with the summary of technical challenges above, the problem of energy requirements for on-body signal processing requires a tradeoff on algorithm complexity and continuous runtime without changing/recharging batteries. Although energy requirements depend on a number of aspects, only a few main items were varied for different application-dependent implementations of the electronics, including computational performance, data storage space and number of sensor terminals. This approach allowed to establish common standards for wireless transmission of data to the user station, the transmission protocol, and algorithm sharing for different applications.

Three different levels of processing performance are used in the project: 1) electronics based on low-power microcontrollers, e.g. based on the TI MSP 430 family[6], 2) systems with medium performance, e.g. based on ARM family 7 processor[7] and 3) systems for advanced processing and service requirements running standard operating systems. In the last category the QBIC[8] system was used (Amft et al., 2004). The MSP-based systems require less energy compared to category 2 electronics, permitting highly miniaturised electronics due to smaller batteries.

Two systems from the low-power category are shown in Fig. 6. The system on the left was developed as a first prototype. This system is used with the band and shirt shown in Fig. 4. The right picture shows a second generation prototype in use with the sensor garment. Theses systems are capable of sampling and processing a small number of sensors and features, e.g. ECG features HR, HRV for more than 20 hours autonomously. MSP-based system are a preferred choice for sensor nodes and have demonstrated their capabilities, e.g. even for frequency-domain feature processing of a low-bandwidth microphone (Stäger et al., 2003).

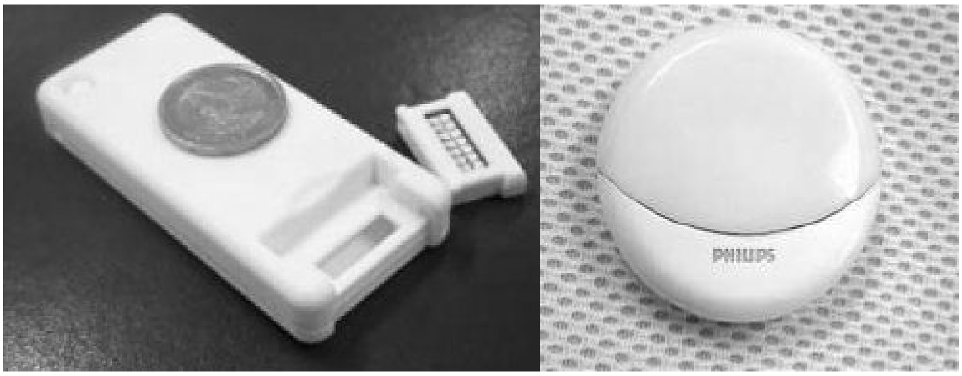

Figure 6: Prototypes of the MyHeart on-body electronics, left: first prototype, right: second prototype (courtesy Philips).

The electronic system is placed into a side pocket of the garment. It must be removed before washing of the textile. This approach has the advantage that the electronics does not need a waterproof seal, however it requires a connector to the garment-based sensors that is manageable by an untrained user. The construction of textile-electronics connectors is a challenging problem since the design must be robust enough to sustain frequent connection cycles, washing and provide multiple connection lines for data and power. Some solutions for textile interfaces have been proposed, e.g. (Linz et al., 2005; Locher, 2006). Further connection approaches are currently under investigation within the project.

[6]http://www.ti.com/msp430
[7]http://www.arm.com/products/CPUs/families/ARM7Family.html
[8]Q-Belt integrated computer (QBIC), http://www.wearable.ethz.ch/qbic.html

3.4 User station and feedback

In the following the MyHeart feedback approach and the utilised user station solutions are briefly summarised.

Direct and indirect feedback The user station provides direct feedback to the user, as a result of the analysis task and optionally indirect feedback which is post-processed by a professional health care service. Algorithms residing at the user station and the on-body electronics process the features for both feedback loops. While the direct feedback is intended as regular and constant service the indirect feedback is provided on demand or as a result of a detection of abnormal trend.

The direct feedback provides trend chart and statistic visualisations for different timescales as well as automatic recommendations depending on the user scenario. E.g. in the PC Take Care a user may have the task assignment to review their personal activity level daily. The system provides weekly averaged trends and automatic messages, e.g. when it detects, by trend forecasting, that a defined goal cannot be reached. The indirect feedback is intended for coaching individuals or groups with special needs.

User station solutions Choice of the user station is specific for each concept, since the device must fulfil different requirements besides the visualisation of feedback information. E.g. for heart failure patients a mobile phone is advisable to automatically contact medical help in case of an emergency. For the PC Take Care a stationary device in the users home is used, which may be shared with other applications. Typical devices include Personal Data Assistants (PDAs) or newly emerging mobile computing gadgets.

3.5 Summary and lessons learnt

This section provided an overview on main technological challenges in the MyHeart project. Starting from a general monitoring, analysis and feedback methodology specific problems for garment-based health monitoring and analysis were presented and relevant sources for further information were indicated. Emphasis was given to common problems for all MyHeart concepts.

From the technical experience gained in the completed project phases several practical issues have been identified that need further evaluation. Relevant items for the garment system part include the improvement of textile electrodes and their positioning, the textile-based network and the wearing comfort of the garment. To achieve good electrode contact a tight fitting was aimed. This raised the difficulty to dress and undress the garment. Furthermore the textile strain sensors for the detection of postures and gestures need further investigation to simplify the interface to a high number of signalling lines, the resistance adaptation method for the electronics and to evaluate applications with regard to the intrinsic sensor hysteresis problem, e.g. found in (Amft et al., 2006) for a standard type of textile strain sensor. For the inertial sensing approach issues with the use of compass sensors (disturbances of the magnetic field orientation) have been identified in literature (Miller et al., 2004). From experiments of the authors it was found that even a table or chair constructed from metal parts interferes with the orientation estimation. This requires careful algorithm design when using these sensors.

In the upcoming project phase a clinical trial will be started. This unveils new challenges for the entire wearable system, e.g. the production of more than 200 wearable systems for different body sizes and both genders, medical certification of the systems and support of the subjects using the devices in the trial.

4 Evolution of MyHeart approach and related work

This section summarises further development within MyHeart. Moreover a brief summary of commercial and research works related to MyHeart are presented. The section is concluded by summarising related projects supported by the European Commission.

4.1 Research in sensing and analysis

After introducing the technical objectives of MyHeart in Section 2, the technical approach and associated challenges for frequently applied sensing and analysis methods was discussed in Section 3. The following part reviews further wearable and textile monitoring and analysis approaches that are currently investigated within the project and provides references to the performed research.

Heart activity Continuous monitoring of heart activity clearly provides the most important information for determining actual cardiac status. Current works aim at the further analysis of features related to the heart activity, e.g. interrelation and prognostics in chronic heart failure patients (Maestri et al., 2005) and further parameters (Folino et al., 2005; Guasti et al., 2005b) as well as relation of cardiac status to lifestyle, e.g. (Quaglini et al., 2005). The integration of analysis algorithms into wearable systems is a technical objective of MyHeart and addressed by, e.g. (Milanesi et al., 2005; Brito et al., 2005).

Sleep and stress As presented before, sleep and stress are two important aspects of quality of life and linked to CVD. MyHeart aims at providing prevention solutions that are applicable during the night too: current work studies sleep behaviour, e.g. (Ferini-Strambi et al., 2005) and the interrelation to wearable systems (Puzzuoli et al., 2005; Mendez et al., 2005). Furthermore the relation to stress was analysed (Guasti et al., 2005a).

Virtual activity trainers Virtual sport trainers address the physical activity improvement in the CardioActive application cluster. Sala et al. (2005) presented a wearable solution.

Neurologic rehabilitation The integration of activity sensing solutions into garments promises convenient textile solutions. Current works aim at optimising textile strain sensors for posture detection and to compensate sensor limitations, e.g. (Giorgino et al., 2006; Lorussi et al., 2005).

Nutrition behaviour Dietary behaviour is strongly interrelated to malnutrition and CVD. Wearable solutions are sought that provide behavioural statistics and are capable to analyse the eating microstructure on-body. Sensing approaches are evaluated that provide such information, e.g. the analysis of chewing activity (Amft et al., 2005b) and gestures associated with foodstuff intake (Amft et al., 2005a). Furthermore the combination of different information sources is investigated (Amft and Tröster, 2005).

Feedback and professional interaction Besides the challenges in establishing psychological effective solutions to continously motivate the user, further solutions simplifying the interaction with professional medical services are required. Villalba et al. (2006) presents an approach to establish a heart failure management system, integrating information acquisition, database management as well as processing and retrieval functions. The system provides interfaces for the patient and professionals.

4.2 Related works and projects

Related work Commercial heart rate and Holter monitoring systems have been developed, e.g. by Polar[9] or Schiller[10]. Reima[11] developed belts and garments for communication and outdoor sports. Complete sensing shirts, integrating various physiological signals are developed by Vivometrics[12] and Sensatex[13]. The Vivometrics' Lifeshirt system is available for research purposes, Sensatex announced field tests of their SmartShirt for 2006. Various

[9] http://ww.polar.fi
[10] http://www.schiller.ch
[11] http://www.reima.com
[12] http://www.vivometrics.com
[13] http://www.sensatex.com

other smart textile systems, e.g. Smart Bra[14], Burton Amp Jacket[15] and carry-on devices, e.g. Body Media Armband[16] been investigated.

Most of the systems and devices realised to date, relied on the sensing and processing of physiologic data. In many cases the monitoring systems are limited either in duration of continuous usage, number of analysed parameters, functionality or wearing comfort. Besides resolving these restrictions, MyHeart aims at providing personalised feedback, including long-term plans and recommendations. Moreover in MyHeart the preventive effectiveness of derived information is evaluated.

Related European activities The MyHeart project is embedded into the Smart Fabrics - Interactive Textile (SFIT) cluster of research and development projects founded by the European Commission[17]. The SFIT cluster targets the realisation of the “e-textile” paradigm by further integration of micro- and nano-technologies into textile solutions. The developed systems shall seamlessly integrate sensing, actuating, processing, communication and power sources.

MyHeart was launched, building partly on the results of Wealthy[18], a project of the European Commission’s fifth framework programme addressing the simultaneous recording of vital signs from textile sensors. A number of projects related to MyHeart were initiated aiming at exploring different applications and future business opportunities, e.g.:

- PROETEX[19]: Development of protection e-textiles for emergency and disaster wear.
- STELLA[20]: Development of stretchable electronics for large textile area applications.
- BIOTEX[21]: Development of bio-sensing textiles to support health management using chemical sensors.
- CONTEXT: Contact-less sensors for continuous heart and muscle monitoring incorporated in textiles.

[14] University of Wollongong, http://www.uow.edu.au
[15] http://www.apple.com, http://www.burton.com
[16] http://www.bodymedia.com
[17] Information about the SFIT activities was presented by A. Lymberis at the Pervasive Health conference 2006, Lucerne, Switzerland and provided to the authors for further dissemination.
[18] http://www.wealthy-ist.com
[19] http://www.proetex.org
[20] http://www.stella-project.eu
[21] http://www.biotex-eu.com

- OFSETH[22]: Integration of optical fibre based sensors into functional textile for extending the capabilities of wearable solutions in health monitoring.
- MERMOTH[23]: Development of a generic medical monitoring system using smart bio-sensors.

Sources for further information Further information on MyHeart can be found on the Internet pages[24]. Information on related projects in the sixth framework programme are available from the European Commission[25].

Acknowledgement

The authors would like to thank all MyHeart project partners for their contribution to this work. MyHeart is a European project funded by the European Commission in the sixth framework programme (IST-2002-507816). This work was supported by the Swiss State Secretariat for Education and Research (SER).

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[22] http://www.ofseth.org
[23] http://www.mermoth.org
[24] http://www.hitech-projects.com/euprojects/myheart
[25] http://cordis.europa.eu/ist/health, http://cordis.europa.eu/ist/mnd

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