Pervasive Healthcare

Paving the Way for a Pervasive, User-centered and Preventive Healthcare Model

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Keywords

Pervasive healthcare, pervasive sensing, pervasive prevention, pervasive technology evaluation, ubiquitous computing

Summary

Objectives: The aging of the population creates pressure on the healthcare systems in various ways. A massive increase of chronic disease conditions and age-related illness are predicted as the dominant forces driving the future health care. The objective of this paper is to present future research demands in pervasive healthcare with the goal to meet the healthcare challenges by paving the way for a pervasive, user-centered and preventive healthcare model.

Methods: This paper presents recent methodological approaches and proposes future research topics in three areas: i) pervasive, continuous and reliable long-term monitoring systems; ii) prevention through pervasive technology as a key element to maintain life-long wellness; and iii) design and evaluation methods for ubiquitous, patient-centric technologies.

Results: Pervasive technology has been identified as a strong asset for achieving the vision of user-centered preventive healthcare. In order to make this vision a reality, new strategies for design, development and evaluation of technology have to find a common denominator and consequently interoperate. Moreover, the potential of pervasive healthcare technologies offers new opportunities beyond traditional disease treatment and may play a major role in prevention, e.g. motivate healthy behavior and disease prevention throughout all stages of life. In this sense, open challenges in future research have to be addressed such as the variability of health indicators between individuals and the manner in which relevant health indicators are provided to the users in order to maximize their motivation to mitigate or prevent unhealthy behaviors. Additionally, collecting evidence that pervasive technology improves health is seen as one of the toughest challenges. Promising approaches are recently introduced, such as "clinical proof-of-concept" and balanced observational studies.

Conclusions: The paper concludes that pervasive healthcare will enable a paradigm shift from the established centralized healthcare model to a pervasive, user-centered and preventive overall lifestyle health management. In order to provide these new opportunities everywhere, anytime and to anyone, future research in the fields of pervasive sensing, pervasive prevention and evaluation of pervasive technology is inevitably needed.

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Methods Inf Med 2010; 49: 67–73
doi: 10.3414/ME09-02-0044
received: October 10, 2009
accepted: November 12, 2009
prepublished: December 8, 2009

1. Introduction

Before the 20th century, medical care was delivered at home, through visits from mobile family physicians who packed the necessary medical technology into a doctor's bag. In the 20th century rare and expensive resources, such as heavy technology and specialist providers, had to be centralized in hospitals to make their utilization effective [1]. Nowadays, the ageing of the population exerts pressure on the healthcare systems in various ways: increasing of chronic diseases and co-morbidity, problems of compliance to medication and lifestyle guidance among the elderly, and the need for long-term care and assistance of elderly people [2]. According to [3], a massive increase of chronic disease conditions and age-related illnesses are predicted as the dominant forces driving the future health care. Driven by quality and cost issues, the healthcare systems have to change radically in the near future from current healthcare professional-centric systems to distributed networked healthcare systems in which the individual becomes an active partner in the care process [4]. According to [5], there is the need to move from managing illness to maintaining wellness. In this transformation, pervasive technologies will play a major role [6]. Research on pervasive computing technologies for healthcare does not aim to replace traditional healthcare but is rather directed towards paving the way for a pervasive, user-centered and preventive healthcare model.

1.1 Pervasive Healthcare Definition

Pervasive healthcare may be defined from two perspectives: i) as the application of pervasive computing technologies for healthcare, and ii) as making healthcare available everywhere, anytime and to anyone [7]. Pervasive healthcare is closely related to biomedical engineering (BME), medical informatics (MI), and ubiquitous computing (UbiComp). BME combines engineering skills with biomedical science to improve diagnostics, treatment, and follow-up. MI processes large sets of health data to optimize use of information in healthcare. UbiComp designs, develops and evaluates the use of new pervasive sensorized systems deployed in large scale. While BME and MI mostly focus on technology to improve the existing health delivery model, pervasive healthcare in contrast tries to change the healthcare delivery model: from doctor-centric to patient-centric, from acute reactive to continuous preventive, from sampling to monitoring [8]. Additionally, while the term "pervasive" stands for the tendency to expand or permeate, "ubiquity" is the property of being omnipresent. In this sense, the ultimate goal of pervasive healthcare is to become a mean for achieving ubiquitous health.

1.2 A Growing Research Community: Pervasive Health Conference

An important action towards pushing forward the state-of-the-art in pervasive healthcare is the identification of this field as a new discipline and consequently promoting the systematic exchange of ideas in a coordinated way. A successful example of this kind of coordination has been presented through the creation of Pervasive Health Conference Series as a forum for promoting discussions in this field. In the past, extended work from that forum was selected and published by this journal to provide a better insight on relevant work done in this field. Example of these works include research related to sensing technologies [9, 10], innovative applications [11, 12] and visionary roadmaps identifying trends and opportunities in this area [8]. Moreover, considering the rapid evolution of this field such as the open research trends identified by Koch and others [13], a new special topic of this journal is presented in this issue including recent results from the last Pervasive Health Conference. This special topic includes, besides this introductory paper, four papers from such conference presenting extended results from multidisciplinary approaches towards pervasive healthcare. These papers, as well as other work presented during Pervasive Health Conference Series, are a clear indication that pervasive health topic is moving towards the constitution of a solid research field sustained by a dynamic and rapidly growing community. The first paper of this list by Katie Siek and Julie Maitland [14] presents a study focused on understanding the financial-related barriers those caregivers of low socioeconomic status encounter when attempting to make dietary behavior change. The second paper by Marco de Sá and Luís Carriço [15] discusses an environment for the development of mobile pervasive therapy artifacts (OmniSCOPE). The remaining two papers focus on some aspects related to innovative treatment of specific diseases. The first one by Marc Bächlin et al. [16] is dealing with a wearable system for providing acoustic cueing to assist Parkinson patients to walk. The second one by Bianying Song et al. [17] presents the construction of a decision support system for teletraining of patients suffering from COPD.

1.3 Future Research Needs

Pervasive healthcare offers both, healthcare professionals and patients, new opportunities. On one side, medical doctors and other healthcare professionals will benefit from diagnostic and therapeutic opportunities far beyond what is possible with today's occasional examinations. They will have access to long-term recordings of physiological data measured in natural environment including patient's activity and the situations to which he has been exposed to. On the other side, patients are empowered to take a more active role in their personal health management and prevention. For example, user feedback or even personal coaching might help a patient to adjust his lifestyle to the requirement of his health [18]. In order to provide health professionals and patients with these new opportunities, future research is needed in these areas:

1. pervasive, continuous and reliable long-term monitoring systems;
2. prevention as the key element to maintain lifelong wellness; and
3. design and evaluation methods for ubiquitous patient-centric technologies.

The main component of the first area corresponds to the improvement of pervasive sensing. A relevant aspect in wearable sensing systems is the trade-off between patients' comfort, sensor unobtrusiveness and signal quality that needs to be addressed in order to improve medical pervasive sensing. This trade-off relationship is further detailed in Section 2. Regarding the second issue, we provide in Section 3 evidence that there is a need for monitoring multiple indicators and a need for developing adaptive systems to enable pervasive prevention. Section 4 highlights the need for a new approach for evaluating Ubicomp Pervasive Health systems.

2. Pervasive Sensing: Patients' comfort and signal quality

Pervasive sensing in healthcare may be defined as a subsystem with two core functionalities: i) continuously sensing of body functions, user's context and environmental parameters as well; ii) delivering the sensed data to a higher level application. An example of pervasive sensing is a unit that continuously senses electrocardiography (ECG) data and body acceleration for an application that estimates physical fitness based on heart rate and user's activity [19].

2.1 Quality Control of Sensor Data

Designers of sensor units are confronted with the trade-off between patient's comfort and sensor signal quality. On the one side, user's acceptance of continuous sensing depends on the level of the user's comfort. For example, dry ECG electrodes incorporated into normal clothes would offer a high level of comfort and user acceptance in comparison to classical wet electrodes which might induce skin irritation during long-term usage [20] or the position and stability of the sensor may influence the relationship between comfort and quality [9, 21]. On the other side, comfortable and unobtrusive sensor technology often renders a continuous high signal quality impossible, e.g. dry ECG electrodes are highly sensitive to motion artifacts which results in a disturbed ECG signal during physical activity [22].

With regards to the trade-off between patient's comfort and signal quality, not only the development of comfortable and reliable sensor technology but also an automatic quality control of the data generated by sensors needs to be addressed. One common approach to tackle low signal quality is to automatically detect and compensate erroneous signals which are commonly referred to as artifacts. Examples include detection of artifacts in ECG data based on changes in the electrode-skin impedance [23] or based on accelerometers [24]. However, in many clinical cases an automatic compensation of artifacts can lead to a false sense of safety since actual corrupted data might look plausible and thereby falsify the interpretation of the data. Moreover, if the signal is not reconstructible, compensation is not possible at all. Hence, in clinical settings it is more useful to automatically indicate the signal quality as an input for later data interpretation and decision making [25].

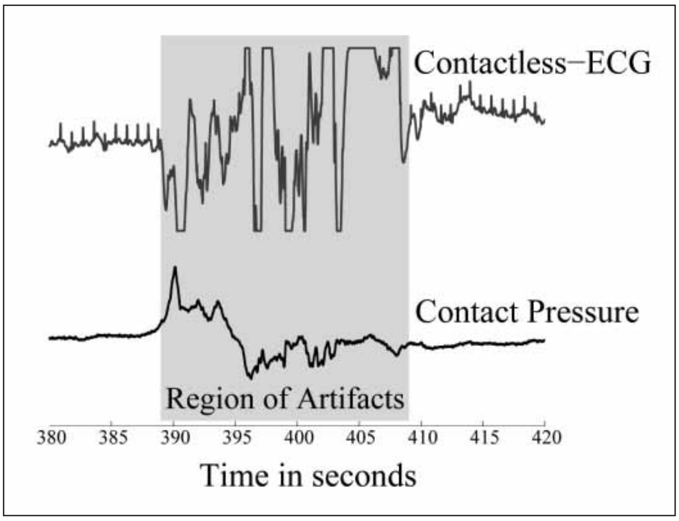

Fig. 1 Contactless ECG signal recorded in a seat with additional contact pressure sensors in the backrest. Changes in the contact pressure indicate that the user is moving which results in a disturbed ECG signal.

2.2 Automatic Appraisal of Signal Quality

Recently, Schumm et al. presented a method that appraises the signal quality in unobtrusive, contact-less ECG sensing to enable automatic medical decision making such as heart rate variability (HRV) analysis [26]. In a seat, contact-less capacitive electrodes were incorporated together with pressure sensors in the backrest. Movements of the person in the seat result in a disturbed ECG signal (▶Fig. 1). The authors propose to transform the problem of appraising the quality of an ECG signal into a classification problem. First, the true signal quality is determined by defining a quality label for an ECG signal. The quality label indicates whether the R-peaks in the contact-less ECG signal were successfully identified in comparison to a conventional ECG system using wet electrodes. Second, a classification model is trained to predict the quality label. The model only incorporates data from the contact-less ECG and if available also other sensor modalities. As a result, the model is able to distinguish between high and low signal quality parts with an average accuracy of 92%. In conclusion, this approach appraises the signal quality of a comfortable but unreliable ECG system by modeling the system behavior. The only prerequisite is the availability of a reliable ground truth system during the model building. Since this approach is not restricted to ECG signals and open to other sensor modalities, it will be helpful to tackle the trade-off between sensor comfort and signal quality in medical pervasive sensing.

3. Pervasive Prevention: Motivate People to Change their Behavior

In the envisioned transformation from managing illness to maintaining wellness, pervasive technologies are foreseen to not only cure sickness, but also promote wellness throughout all stages of life. This is in line with how the World Health Organization (WHO) defines health in the preamble to its constitution, namely as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" [27]. In this regard, pervasive technologies offer a new healthcare opportunity by exploiting emerging consumer electronic devices to motivate healthy behavior. Intille brought up the idea of persuasive technology to motivate healthy ageing [28]. Morris et al. envision that the mobile phone will emerge as the preferred personal coach of the 21st century [29].

As prevention becomes more important, pervasive health assistants may become more and more common as lifestyle assistants. These assistants differ by the timescale on which they operate as well as the sensing domains. First, they have to operate continuously, even before any clinical event. Second, instead of monitoring one medical parameter like ECG, lifestyle assistants will become multimodal since many aspects influence health prospects and well-being. As a consequence they will fuse information coming from physical and physiological sensors, but they will also consider cognitive, social and environmental factors [30].

3.1 Preventing Mental Disorders

A continuous multimodal monitoring is of particular importance for preventing mental disorders. A relevant example is prevention of clinical depression. According to the World Health Organization, major depressions affect around 25% of all people at some time during their life. These disorders are universal – affecting all countries and societies, and individuals at all ages. The negative direct and indirect impact on economy and on the quality of life of individuals and families is massive. An early assessment of risk factors or an early detection of negative vital signs could significantly reduce this cost through early prevention [31].

Another relevant example of disease prevention, based on continuous monitoring technologies, is the case of chronic stress. Recently, the European Foundation for the Improvement of Living and Working Conditions called the attention on increasing level of mental disorders due to work-related stress. The workplace has changed dramatically due to globalization, use of new information and communication technology, resulting in an increased mental workload. Work-related stress was found to be the second most common work-related health problem across the EU15 [32]. Work-related chronic stress occurs when there is a mismatch between job demands and the capabilities, resources or needs of the worker. If the worker is not able to recover, long-term damage may result in the development of mental disorders [33]. Pervasive healthcare offers new opportunities to prevent long-term damage by continuously monitoring stress levels and providing just-in-time feedback increasing patients awareness for improving self-management of disease [34, 35] (e.g. through a "Personal Stress Prevention Assistant").

Pervasive healthcare research in the field of stress prevention is still at an exploratory stage. One example is the exploratory research project "Mobile Heart Health" which aims to detect early signs of stress triggered by physiological or contextual changes and provide just-in-time mobile coaching [29]. In that project, indicators of stress are assessed by changes in heart rate variability or by contextual shifts of the user, such as changing the location. When the system detects changes in stress levels, feedback appears on the mobile phone. Such feedback may encourage breathing or physical relaxation exercises. In conclusion two important future research demands are highlighted. First, a hybrid stress detection approach involving multiple physiological stress indicators would enable more accurate stress detection. Second, adaptive systems are needed to deal with the huge variability of stress indicators between individuals.

Both demands, multiple indicators and adaptive systems, are approached in the recent works of Setz et al. and Arnrich et al. [34, 35]. Here two stress factors relevant at the workplace were under investigation: high cognitive load under time pressure and psychosocial stress induced by social-evaluative threat. In the experiments, multiple physiological stress indicators including ECG, breathing, body movement, electrodermal activity, and sitting behavior on a chair where investigated. Up to now the authors investigated changes in heart rate variability, electrodermal activity and sitting behavior as indicators of stress. Similar to the preliminary results of the "Mobile Heart Health" project, the stress indicators varied across the individuals significantly. In order to approach these different reactions of individuals to stress, a self-organizing map which is able to adapt to local cluster structures was employed in Arnrich et al. [35]. In conclusion, the authors confirm the need of adaptive systems to deal with the variability of stress responses between individuals and hence the need of a sufficiently large study population to capture this variability.

3.2 Persuasive User Interfaces

In both of the previous examples related to clinical depression and stress, the use of pervasive sensing technologies can be a relevant asset for revealing early symptoms, and thereby preventing the increase of unhealthy trends. Moreover, besides the understanding of what the sensing technologies can do for patients, an important issue refers to the way the sensed information is used to mitigate or prevent unhealthy behaviors. Depending on the adequateness of use of that information, the awareness of personal state can increase or decrease together with the motivation of patients for engaging in their own disease management [36]. A relevant aspect to consider in this sense is the patient initiative (or lack of it) for accessing his health-related information. In general there are two main approaches for this: the first one refers to patient-initiated operations where the patient has usually strong self-motivation for proactively accessing his personal information, and the second refers to system-initiated operations where the patient's awareness of health status is triggered by occurrence of new health-related events in the form of systematic prompts or messages. In the former case, it is common that if information is not presented adequately in a contextualized way, the patient may underestimate the value of the information or simply ignore it.

A promising approach towards provisioning of relevant health information in both, patients and system-initiated modalities is the use of persuasive user interfaces [28, 37]. These interfaces consider different elements of the context such as the patients' evolving profile, the current situation and other motivational dynamics (e.g. related to social, community-oriented benefits [38] or disease-specific characteristics [39]) to maximize motivation of patients towards the improvement of their health habits and self-treatment. Thus far, the research in this direction has been focused mostly on aspects related to the personalization of persuasion, based on patients' models, specific diseases, etc. However, further research still needs to identify how the disease/profile-specific findings could be extrapolated to different diseases and wider patients groups, i.e. what can be generalized and what has to remain specific.

4. Pervasive Technology Evaluation: Investigate Evidence for Improvement in Health

In a literature review, Orwat et al. provide an overview of recent developments and implementations of pervasive computing systems in health care [40]. In a quantitative analysis, 67 distinct systems were categorized into project status (prototype, trial, regular operation), health care settings (home, clinical, ambulatory), user groups (health care professionals, patients), improvement aims (organizational, medical), and systems features (components, data gathering and transmission, system functions). Qualitative analyses were performed on deployment issues, privacy and security issues, and financial issues. The authors conclude that most systems are still in their prototype stages and that a systematic evaluation of the effectiveness and efficiency of pervasive computing systems is inevitably needed to enable the diffusion of pervasive technologies into health care. In the same direction, Dishman identified a strong need for adequately powered, replicated clinical efficacy and outcome studies [5]. However, he complains that the research infrastructure designed to carry out these kinds of clinical studies is not available yet, i.e. standardized methods need to be developed to compare conventional episodic examinations with continuous ones. In this sense, addressing the fundamental challenge for collecting evidence that pervasive technology improves health is seen as one of the toughest challenges for pervasive health [7].

4.1 Incompatibility of Medical and Pervasive Computing Evaluation

In medical research, an experimental evaluation (often referred to as clinical trial) is a pre-specified investigation performed under standardized conditions. Here, the researcher controls the events of interest and examines the effects of the interventions (e.g. comparison of drug therapy vs. no treatment). In order to avoid that both groups differ in any systematic way which might affect the outcome, the common approach is to allocate treatment to subjects as determined at random. In addition, often a further source of bias – the researcher's knowledge of whether a subject has received the treatment or not – is eliminated by conducting double-blinded clinical trials where neither the medical stuff nor the participants know whether treatment or control is applied [41]. Such strong evidence is virtually impossible to obtain in pervasive healthcare as it currently stands.

In pervasive computing, typical evaluation is based on technical proof-of-concept where researchers design and evaluate prototypes of new technology. The methodology used to carry out these kinds of evaluations is often still the same as described 15 years ago in [42]: debug the viability of working prototypes in daily use where ourselves and few colleagues serve as test subjects. From a medical perspective, such a technical proof-of-concept is clearly not acceptable for introducing new technologies for treatment.

4.2 First Steps Towards Evaluating Pervasive Health Technology

In order to strike a balance between clinical trials and a technical proof-of-concept, Bardram proposed a methodological approach and named it clinical proof-of-concept [8]. Here, a working prototype should be used by real users for a sufficient period of time. Collecting evidence that the technology seems promising in addressing its specific goal would typically be qualitative in nature, involving observations, questionnaires, studies of perceived usefulness and usability. If possible, also more quantitative measures of clinical effect would be included.

Inspiration for designing a research infrastructure to evaluate pervasive technology in healthcare might also come from medicine itself. One has to consider that clinical trials are only applicable for treatments that can be well standardized and where the experimenter can control the events of interest. As a result, areas of epidemiological research are not amenable to being investigated by clinical trials, e.g. passive smoking and lung cancer, alcohol consumption and suicide, etc. [41]. Based on these considerations and additional ethical concerns, observational studies are employed to estimate the effects of a treatment for subjects who were not randomly assigned to treatment or control. The fundamental objective to using observational clinical data for comparing treatments is that many uncontrolled variables affect the outcome and not just one factor for alternative treatment as assumed in clinical trials [43]. Since an observational study with non-randomly assigned treatment can be biased if the patient characteristics are different between treatment and control, in recent years a class of multivariate statistical methods used for controlling such selection biases has been applied increasingly, e.g. by Arnrich et al. [44]. These balancing scores identify patients with similar chances of receiving treatment or control retrospectively. As a result, patients with similar balancing scores but different treatment provide an unbiased estimate of the average treatment effect [45]. Considering that the evaluation of pervasive healthcare faces similar challenges as areas of epidemiological research (treatment cannot be well standardized, experimenter cannot control the events of interest), balanced observational studies might be a valuable tool to collect evidences that pervasive technology improves health.

Even though a holistic approach for evaluating the effect of pervasive health technology effectiveness is still missing, a first step towards this has been taken by identifying different evaluation means borrowed from different fields (e.g. medical sciences and human-computer interaction) and adapted for pervasive health systems. Examples of this include evaluation of perceived privacy and security in pervasive health systems [46], evaluation of user acceptance and technology adoption [47], and multidisciplinary clinical evaluation methods [48] among others. An open question remains whether those adaptations would continue to be valid for the coming generations of pervasive health systems or if the notion of health management itself will be fundamentally altered by the new pervasive technologies implying a complete re-thinking of healthcare provisioning and the evaluation of its effectiveness.

5. Concluding Remarks

The ageing of the population creates pressure on the healthcare systems in various ways. A massive increase of chronic disease conditions and age-related illness are predicted as the dominant forces driving the future health care. In the envisioned transformation of the healthcare systems from managing illness to maintaining wellness, research on pervasive technologies aims to pave the way for a pervasive, user-centered and preventive healthcare model which is available everywhere, anytime and to anyone. Healthcare professionals will profit from long-term monitoring in natural environments while patients are empowered to take a more active role in their personal health management. In order to provide these new opportunities for both healthcare professionals and patients, future research is needed in the fields of pervasive sensing, pervasive prevention and evaluation of pervasive technology in healthcare. The open research questions in pervasive healthcare to be solved are for sure multiple. This paper highlights some of these challenges specifically regarding reliability of long-term monitoring systems, the role of prevention as a key element to maintain lifelong wellness and the need of more advanced design and evaluation methods for ubiquitous patient centric technologies.

Future pervasive health systems are foreseen as the key enabler for pushing the paradigm shift from the established centralized healthcare model to a user-centered and preventive overall lifestyle health management. The ongoing projects in academia and industry will pave the way towards making healthcare available everywhere, anytime and to anyone.

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