Pervasive Healthcare as a Scientific Discipline

J. E. Bardram
IT University of Copenhagen, Copenhagen, Denmark

Summary

Objective: The OECD countries are facing a set of core challenges; an increasing elderly population; increasing number of chronic and lifestyle-related diseases; expanding scope of what medicine can do; and increasing lack of medical professionals. Pervasive healthcare asks how pervasive computing technology can be designed to meet these challenges.
The objective of this paper is to discuss 'pervasive healthcare' as a research field and tries to establish how novel and distinct it is, compared to related work within biomedical engineering, medical informatics, and ubiquitous computing.
Methods: The paper presents the research questions, approach, technologies, and methods of pervasive healthcare and discusses these in comparison to those of other related scientific disciplines.
Results: A set of central research themes are presented; monitoring and body sensor networks; pervasive assistive technologies; pervasive computing for hospitals; and preventive and persuasive technologies. Two projects illustrate the kind of research being done in pervasive healthcare. The first project is targeted at home-based monitoring of hypertension; the second project is designing context-aware technologies for hospitals. Both projects approach the healthcare challenges in a new way, apply a new type of research method, and come up with new kinds of technological solutions.
'Clinical proof-of-concept' is recommended as a new method for pervasive healthcare research; the method helps design and test pervasive healthcare technologies, and in ascertaining their clinical potential before large-scale clinical tests are needed.
Conclusion: The paper concludes that pervasive healthcare as a research field and agenda is novel; it is addressing new emerging research questions, represents a novel approach, designs new types of technologies, and applies a new kind of research method.

Keywords

Pervasive healthcare, clinical proof-of-concept, research, method, pervasive computing, ubiquitous computing

Methods Inf Med 2008; 47: 178–185

doi:10.3414/ME9107

1. Introduction

This paper seeks to investigate whether 'pervasive healthcare' as a research field is something new or is just a new label for existing research[a]. In order to investigate this question, we need to consider what we mean with a 'research field' and what we mean by 'new'. To narrow down the first question, there is a list of questions which we need to address, such as:

- What are the challenges which are addressed by the field?
- What are the core research questions? And why are these worth investigating?
- Who will benefit and/or be affected by the solutions?
- What are the methods used to address the research questions? And how do we measure success?
- What is the short-term, mid-term, and long-term impact of this research?
- What types of results do we expect? What are the prototypical solutions?
- How is the field related to – and distinct from – other research fields?
- And – what will happen if we do not do this research?

These are very large and overreaching questions which are not easily answered. This paper will address these questions, but the real goal of the paper is also to introduce these questions and provide some direction for their answers for other to pick up on.

The second question – what actually constitutes something new – actually turned out to be a much harder question. Often a 'new' contribution is only recognized historically, i.e. when looking back in the history of ideas, one is able to recognize that a new idea emerged at a certain point in time. However, when you are in this point in time, it is often very difficult to see the novelty of the idea. The fact that the heliocentrism world view proposed by Galileo was not recognized within his lifetime is a classic example. The Danish philosopher Søren Kierkegaard has said that "Life is lived forward, but understood backwards". To illustrate this paradox, we can think of cars. When we see a brand-new Ferrari, there is little doubt that this is a car; when we see a horse carriage from the 18th century, there is also little doubt that this is a horse carriage. However, when we see some of the first automobiles ever made, these look very much like a horse carriage equipped with a supplementary engine. Today we are not in doubt – these were the first examples of cars. In the time they were made, they were just carriages. My main argument is precisely that 'pervasive healthcare' is right now a horse carriage with a supplementary engine; right now it is difficult to see what is new, but I'm certain that when looking back in the years to come, 'pervasive healthcare' will be recognized as a new scientific approach. This paper will try to evolve this argument.

2. Challenges, Questions, and Approach

Pervasive healthcare [1] takes its outset in the rising health challenges that the OECD countries are facing in the near future. These challenges are well-known to many readers, and I will only summarize them here[b]:

[a] This paper is based on the keynote talk that I gave at the 2008 Conference on Pervasive Health in Tampere, Finland. The original title of the talk was "Is 'Pervasive Healthcare' old wine on a new bottle – or is it a real, but emerging, research discipline?" Slides from the talk can be found at SlideShare.

[b] More details on these challenges and their relation to pervasive healthcare research are discussed by Kaye and Zitzelberger in [2].

- The demographic development is predicting a huge increase in the ratio of elderly people as compared to the working set of citizens.
- Chronic diseases and healthcare costs are increasing as people grow older.
- Current lifestyles (e.g. smoking, obesity, and inactivity) contribute toward increased prevalence of chronic degenerative diseases.
- Constantly expanding scope of what medicine can do thanks to innovative medicine and healthcare technologies, increases healthcare cost and average life expectancy.
- There is an increasing lack of clinical professionals due to retirement and general small numbers of medical and nursing students.

All of these challenges interact, which means that in common they represent a fundamental healthcare challenge to all OECD countries – irrespective of their welfare model.

The question that the research field of pervasive healthcare is trying to ask is basically how pervasive computing technologies can help mitigate these challenges. Apparently, this may seem like a pure 'applied' research field – i.e. how to apply something existing – pervasive computing technologies – to solve a specific 'problem' in healthcare. This is, however, far from the case. First of all, 'pervasive computing' in itself is not anything well-defined; pervasive computing is a very active research area combining electrical engineering, computer science, and human factors research. Hence, researching and developing pervasive computing technologies is currently on-going, and the input is coming from a number of application areas, including healthcare. Second, the 'healthcare problem' is an ill-defined problem, and it will require fundamental research to uncover the concepts and solutions for mitigating the complex web of challenges listed above. Hence, in combination, pervasive healthcare is doing research on two flanks simultaneously; researching new pervasive computing technologies appropriate for the healthcare environment, while also researching new solutions and approaches for mitigating the fundamental healthcare challenges. As such, pervasive healthcare certainly has positioned itself within a demanding research agenda.

Clearly the challenges listed above are recognized within other research disciplines and fields, who – fortunately – are also addressing them and are suggesting solutions. Biomedical engineering (BME) combines the design and problem-solving skills of engineering with the medical and biological science to help improve patient healthcare and the quality of life of healthy individuals. Examples of concrete applications of biomedical engineering are biocompatible prostheses, medical devices, diagnostic devices and imaging equipment such as EEGs and MRIs, and pharmaceutical drugs. Hence, BME is targeted at improving disease diagnostics, treatment, and follow-up. Medical informatics (MI), on the other hand, deals with the resources, devices and methods required to optimize the acquisition, storage, retrieval and use of information in healthcare. Health informatics tools include not only computers but also clinical guidelines, formal medical terminologies, and information and communication systems. In essence, MI is targeted at information processing of large sets of health data, including e.g. electronic patient records. In addition to these more technical health research disciplines, areas like hospital management, architecture, and production engineering all address the overall challenge of delivering more and better healthcare services with less resources. Finally, a strong sister discipline to pervasive healthcare is the research done within pervasive and ubiquitous computing (UbiComp). UbiComp is concerned with the study, design, and implementation of new types of embedded, mobile, pro-active, context-aware, collaborative, and sensor systems, which are deployed in large scale.

Pervasive healthcare is closely related to BME, MI, and UbiComp and many researchers are active in several of these fields. Pervasive healthcare has, nevertheless, a set of scientific goals and approaches, which also makes it fundamentally different and distinctive.

Overall, I would argue that pervasive healthcare is part of an overall approach,

Acute	→	Continous
Hospitalization	→	Home & out-patient
Reactive	→	Pro-active & Preventive
IT	→	Assistive Technology
Centralized	→	Pervasive
Sampling	→	Monitoring
Doctor-centric	→	Patient-centric

Fig. 1 The pervasive healthcare approach – changing focus from a centralized, reactive, and information-focused approach to a decentralized, preventive, and assistive approach

which is trying to alter the Western healthcare service delivery model. The approach is to move from a centralized model with highly specialized medical professional inside hospitals that treat ill patients, to a much more decentralized model where people themselves are active participants in caring for their own well-being. Eric Dishman [3] has used the metaphor of the outdated mainframe computer to describe the current model of healthcare service delivery – the mainframe being equivalent to the hospital – and has used this metaphor to argue for moving to a much more decentralized and personal healthcare model equivalent to the inter-networked personal computer.

Hence, pervasive healthcare technologies are designed and developed to support this decentralized approach, which can be described along a set of distinctive dimensions, as illustrated in Figure 1. First, pervasive healthcare technologies seek to support continuous well-being, treatment, and care of people rather than focus on technologies for acute treatment and care. Second, focus is on moving patient treatment and care from hospitalization to home-based or out-patient treatment. This is already a movement, which is accelerating due to technological improvement in e.g. ambulatory surgery. Pervasive healthcare technologies will help improve this process – both by providing technologies for patient self-care, and by providing technologies for the clinicians to reach out to home-based patients. Third, instead of periodic sampling done inside hospitals (e.g. blood sampling or X-ray imaging), continuous monitoring done automatically or by the patient him or herself combined with decision support systems, will enable pro-active and preventive types of diagnosis, early detection, and treatment of various diseases. Fourth, pervasive healthcare technologies will help patients to deal with their own well-being, health, and illness to a much larger degree and most pervasive healthcare technologies are hence patient-centric rather than designed for clinical professionals. Finally, much research into the use of information and communication technology (ICT) in the healthcare sector has been focusing on information processing, storage, integration, modeling, and presentation. In short, focus has to a large degree been on creation of information technology for healthcare. In contrast, the types of technologies that pervasive healthcare research targets can be characterized as assistive technologies aiming at helping citizens to stay well physically, mentally, and socially; to self-manage any disease they might have, and in general assist people in continuous health-related activities. The movement from information technology to assistive technology also applies when creating pervasive computing support for clinicians inside hospitals – the focus is not on information processing (like medical records) but more on assisting clinicians in their daily work using embedded, wireless, mobile, ambient technologies inside the hospital. Section 4 presents some examples to illustrate these dimensions.

With the danger of generalizing, I would claim that most work within BME and MI has been – and to a large degree still is – focused on technologies for the centralized, existing health service delivery model (the left side of Fig. 1). Most BME technologies are made for clinicians for diagnostic purposes and for treatment for acute ill patients inside hospitals. Even extremely 'personal' devices like pacemakers or artificial heart valves are – one could argue – made for clinicians to treat acutely ill patients. Similarly, MI technologies, classifications, and terminologies are made for clinicians and administrators operating inside large healthcare organizations, like hospitals or government institutions. They focus on clinical information processing and decision making, and are often designed in a very centralized way. None of these systems are made for patients, for home-based treatment, or assisted living.

It is in supporting the movement from left to right in Figure 1 that pervasive healthcare technologies exist – and where they address new research challenges and questions with a new approach. Fortunately, many researchers with a background in BME and MI are now joining this research agenda.

At a first glance, the research approach of pervasive healthcare may sound like technologies focusing solely on empowering the patient to engage much more independently in his or her own health management. This is, however, not the complete picture; there are two sides of this coin. Hospitals and other more or less centralized healthcare facilities would still be fundamental to the treatment of patients. But for these institutions to function in this de-centralized and patient-empowered environment, they too need to change the way they organize their services. Hence, an important part of pervasive healthcare is to investigate how pervasive computing technologies can help improve the organization of patient treatment inside hospitals, as well as the collaboration between the home-based patients and the hospital. For example, patients may be hospitalized at home, which sets up a range of requirements for remote monitoring, diagnosis, treatment, care, and communication.

3. Research

Research in pervasive healthcare is already taking many forms. In this section I will present and discuss some of the core research themes, which are addressed. Some of them are already rather mature and have achieved substantial results. Monitoring and body sensor networks, for example, are very active research themes and the technologies are already being deployed in clinical trials. Other themes are much more preliminary and still present a lot of open questions. For example, devising persuasive technologies, which would help people cope with health-related challenges in their lives is a research theme that indeed looks important and promising, but which nobody really knows how to actually execute on. In this paper I have chosen to focus on monitoring, assistive technologies, clinical support systems, and preventive technologies. But more themes exist, and are emerging.

3.1 Monitoring and Body Sensor Networks

Creating technologies for monitoring and creating body sensor networks has been the most active and successful research theme within pervasive healthcare – so far. One strand of work is dedicated to achieving reliable monitoring of health signs like blood pressure, ECG, heart rate, skin conductivity, blood sugar, and similar. The main challenge has been to design and develop reliable yet non-intrusive, wearable sensors, which can be used by a layman. The goal has been to create a platform for continuous monitoring, because substantial clinical evidence indicates that continuous monitoring of certain vital signs can work as early detector of different chronic diseases like hypertension, congestive heart failure, diabetes, dementia, and epilepsy. A related strand is to make sure that this sensor and monitoring technology works together in a distributed infrastructure. This research relates to research within general sensor networks, and has been dedicated to the design and development of health-specific body sensor networks. Resilience, fail-over, network topology, wireless communication, protocols, and real-time data management are important issues in this strand of research.

Body sensor network research seeks to move existing sampling technologies and their use from the laboratories inside hospitals out into the hands of the patients. In addition, a third strand of research seeks to devise technologies and approaches for monitoring and recognizing higher-order behavioral traits. For example, detecting activities of daily living (ADL) based on sensor networks and machine learning approaches has been the topic of several research groups. The goal is to reason about the functioning of an individual, and use this information for early warnings, safety, prevention, and assistance. For example, detecting early signs of dementia, monitoring falls in the home of elderly people, and helping people with dementia to wash hands or remember conversations.

The state of the art is that the first prototypes have been developed, which can be used in larger clinical trials. For example, the MyHeart technology [4] is now being tried out with real patients and the Intel Mobile Sensing Platform (Intel MSP) is being used as a health monitoring infrastructure in different academic research projects [5]. Also, the first types of products are being commercialized – even though many of these are advertised as "wellness technologies" and not as health monitoring devices. One example is the Pulsar monitoring equipment [6].

3.2 Pervasive Assistive Technologies

Assistive technology is a generic term that includes assistive, adaptive, and rehabilitative devices and the process used in selecting, locating, and using them. There is an increasing focus on using pervasive computing technologies for assistive technologies[c].

A core focus within pervasive assistive technologies is to help people stay independent while growing old. Whereas traditional assisted living focused on promoting greater independence for people with disabilities by enabling them to perform tasks that they were formerly unable to accomplish, the pervasive healthcare approach is to support people in general – elderly, ill, disabled, or even well people – to live an independent, well-functioning life with respect to wellness, health, safety, and social interaction.

A number of research projects have been addressing these issues. For example, technologies for independent living includes medication reminder systems, tele-monitoring systems, automatic watering of plants, and cooking reminder systems, as well as safety systems for detecting falls, dehydration, medication errors, gas and electricity hazards, and automatic access control to the house. In addition to these kinds of health and safety systems, a number of researchers have also been addressing how to improve the social life of elderly citizens who increasingly are living alone. Systems for social TV sharing, messaging, media sharing, and peripheral awareness have been suggested – and these systems are in many respects not solely designed for elderly people.

3.3 Pervasive Computing for Hospitals

Contemporary computing technology is to a large extent designed for office use; networked personal computers, which are used at a desk for writing, accounting, communication, or information management. Because the working environment and the nature of the tasks being executed inside a hospital are very different from an office, current technology has turned out to fit very poorly to hospitals.

A central research agenda within pervasive healthcare is to research new kinds of pervasive computing technologies which are suited for hospitals in general, and in particular for supporting out-patient and home-based treatment of patients admitted to the hospital. Focus is on creating computer support embedded in the physical hospital environment, creating context-aware applications, supporting mobility and collaboration, and design capture and access systems for clinical work. For example, systems are designed, which allow clinical personnel easy and context-aware access to relevant clinical data in a specific situation. Focus is on easy but secure access to data without cumbersome login procedures, and fast navigation in the large data sets associated with patient treatment. Other systems are designed to use audio, video, and context sensing to capture all activity inside operating rooms for easy documentation and later review. Context-aware systems are designed to help clinicians to coordinate their work in an efficient manner using both explicit as well as implicit communication modalities while working in a safety-critical environment like an operating room. And systems are using sensor technology and machine reasoning to ensure patient safety during surgery or in medication.

3.4 Preventive and Persuasive Technologies

When looking at the fundamental challenges posed to the OECD countries, the strongest promise – and hope – for the pervasive healthcare technologies lies in preventive and persuasive technologies. Preventive technologies are systems (both technical, organizational, and social), which try to mitigate diseases on a early stage in order to prevent them from occurring, or at least try to delay the onset of the disease. Much work in the monitoring area of pervasive healthcare is targeted towards preventive efforts. Many medical studies have, for example, shown that continuous monitoring of blood pressure has a positive impact on reducing the risk for hypertension and congestive heart failure. Similarly, continuous monitoring of blood sugar and accurate dosage of insulin has proved to reduce the severity of the typical complications that diabetic patients encounter.

Monitoring, however, is seldom sufficient. A large proportion of the diseases that people suffer from (hypertension, diabetes, heart diseases, etc.) are either directly caused or severely aggravated by inappropriate lifestyles related to smoking, drinking, inactivity, and stress – and the best cure seems to be changing people's behavior. Systems, which seek to alter people's behavior are called persuasive technologies. Persuading people to change behavior is not easy and the creation of these kinds of technologies is still in a very preliminary stage with very few specific ideas, concepts, or designs. Examples include making context-aware signs that encourage people to take the stairs rather than the lift; mobile phones that encourage people to walk more (using the mobile phone as a pedometer); and a social walking game among teenage girls using social web technology and mobile phones to access the game.

[c] In Europe, this is termed "Ambient Assisted Living" (AAL) because the European term for pervasive computing typically has been ambient intelligence.

Fig. 2
A patient using the home-based monitoring system in a briefcase for monitoring her blood pressure

4. Examples

To illustrate my arguments I will provide two examples of research project into pervasive healthcare. These examples serve a double purpose: First they act as prototypical examples of the kind of research and the methods applied in pervasive healthcare. Second, they seek to illustrate that this kind of research may at a first glance look like existing and related research within other disciplines. But just like the carriages with an engine that later were recognized as cars, I hope that this kind of research will be recognized as having a different focus and approach in important areas.

4.1 Home-based Monitoring of Vital Signs

The first project is concerned with home-based monitoring of hypertensive patients. Hypertension is a direct cause of a number of heart diseases, including congestive heart failure and stroke, and substantial clinical evidence indicates, that frequent blood pressure monitoring helps prevent hypertension [7]. For this reason, many pervasive healthcare projects have addressed hypertension. This project was done in 2002 when state-of-the-art blood pressure monitoring was based on a cuff. Few other technologies existed –intravenous pressure sensors – but were either research prototypes or only working inside a clinic. Our goal was to deploy the technology in a limited pilot study. The technology for home-based monitoring hence consisted of a suitcase with a traditional blood pressure monitor, a PDA, and a GSM modem as illustrated in Figure 2.

In this project, the patients were given the technology by their general practitioner (GP). The system had three main features: i) it allowed the patient to measure the blood pressure several times a day and this data was sent to a central server for the GP to observe; ii) the GP could prescribe medicines and the patient could indicate that (s)he was complying to the prescription; and iii) it enabled communication between the patient and the GP, using both text and voice messaging.

We carried out a series of interviews and field studies of this home-based monitoring and treatment system, considering issues of medical treatment, division of work, communication, patient self-understanding, and technology [8]. Most medical studies of home-based monitoring of hypertension provide evidence that this kind of monitoring provides more accurate measurements. Our findings emphasized, however, that the relationship between the GP and the patient changed when a new computer-mediated home-based treatment for hypertension was introduced. More specifically, we found four specific aspects of this transformation caused by pervasive monitoring and treatment technology:

- A new division of work emerged, which transferred the act of monitoring and interpreting the blood pressure data from the GP to the patient.
- The medical treatment of hypertension and the life quality of the patient was improved. However, new demands for monitoring the incoming data and the patient's progression in treatment were inflicted upon the GP.
- The communication pattern between the patient and GP was fundamentally changed from a contextual rich conversation to an asynchronous message exchange.
- Because the patient was more involved in the monitoring and treatment of hypertension, he or she became more self-aware on the nature of high blood pressure and what affects it.

Now, why does this project represent pervasive healthcare and not e.g. medical informatics or telemedicine? In general because the focus of the project and the studies was concerned about the transformation of the delivery of healthcare services between the patient and the GP, and more specifically because we were able to study and foster patient self-consciousness in his or her own hypertension treatment. Even though the areas are overlapping, this focus is still different from the medical treatment (using telecommunication technology or not) or medical data management during treatment, which would have been the focus for telemedicine and medical informatics research. Thus, even though the technology in Figure 2 clearly looks bulky and not at all 'pervasive', we still consider this to be a good example of one of the first 'cars' within pervasive healthcare. From a biomedical engineering perspective, the lessons from this project can help us design and build new types of blood pressure monitors, which incorporate support for communication, medication, and sharing of medical data – and hopefully also improve the form factor.

4.2 Pervasive Computing in Hospitals

The second project – called the "Interactive Hospital" project – was concerned with the design and development of pervasive computing technology for hospitals [9]. More specifically, the aim was to build context-aware technologies that support distributed social awareness inside the hospital, communication, and coordination before, during, and after surgery. The focus was on building hospital technologies which were embedded inside the hospital structure, and were using technologies like RFID location tracking of people and patients, large interactive displays embedded in the walls of the hospital, mobile phones and PDAs, and video media spaces. A picture of the technology deployed at an operating ward is shown in Figure 3. Three systems were built and deployed inside a hospital: AwareMedia, which is the software running on the large interactive displays; AwarePhone, which is the mobile unit; and the context-aware and location tracking system.

Fig. 3 The AwareMedia and the AwarePhone deployed and used for coordination of surgeries at an operating ward

The project has demonstrated that pervasive computing concepts and technologies are suitable for clinical work inside hospitals. Due to the nomadic, collaborative, and multi-tasking nature of clinical work, ordinary PCs and terminals tied to desks and offices are not particularly appropriate for clinical work. In contrast, mobile units, large wall-based displays, location tracking, and seamless multi-modal communication are a better match to hospitals.

Again – why does this project represent pervasive healthcare and not e.g. medical informatics? For a couple of reasons. First, because the project was conducting research into pervasive computing technologies. As stated in the introduction, pervasive healthcare operates on two flanks, where the one is core technology research into pervasive computing based on the challenges arising from e.g. healthcare. We are well aware that the technologies in Figure 3 in few years will look very bulky and very far from what I have described as "embedded interactive walls" inside a hospital. But again, we are also very convinced that this is a nice example of one of the first 'cars' within pervasive healthcare for hospitals. Second, because the systems were not concerned with medical information management, which – in this case – would deal with operation planning, patient treatment, documenting surgery, estimating production, administrative reporting to HMOs, etc. Actually, patients barely appeared in the systems at all. Focus was to design technologies, which enabled the clinic – in this case the operating ward responsible also for acute and outpatient treatment – to organize and improve their work practices.

5. Clinical Proof-of-concept

A core characteristic of a scientific discipline is the kind of methods used to address its research questions. Research methods serve a double purpose; on the one hand they specify an approach which is suited to address the questions raised by the scientific discipline; on the other hand they specify how success is measured. For this double reason, research methods are of utmost importance for a research discipline.

There is not a one-to-one relationship between research fields and methods; a research field may apply many different research methods, and the same research method is used in many different fields. For example, the field of pervasive computing applies many research methods ranging from ethnography, to qualitative methods, to field experiments, to quantitative metrics. Just like pervasive computing applies many different research methods to address different parts of the research question, so is pervasive healthcare a highly multi-methodological research agenda.

Nevertheless, some methodological approaches are more 'at home' within a scientific discipline than others; field studies and participant observation originate from ethnography; randomized clinical trials and evidence-based medicine originate from medicine, and quantitative metrics and performance analysis originate from computer science. Here, I want to suggest that a methodological approach, which I have labeled 'clinical proof-of-concept' should be core to pervasive healthcare research. This method strikes a balance between two extremes; technical proof-of-concept and a clinical trial.

A 'technical proof-of-concept' has been the prevalent method for ubiquitous computing and was defined by Marc Weiser as "*the construction of working prototypes of the necessary infrastructure in sufficient quality to debug the viability of the system in daily use; ourselves and a few colleagues serving as guinea pigs*" [10].

Looking at the research questions posed by pervasive healthcare, proof-of-concept seems to be lacking some rigor in order to make sure that the technologies solve health-related challenges. We would never be able to understand or evaluate if a technical prototype for elderly people would be

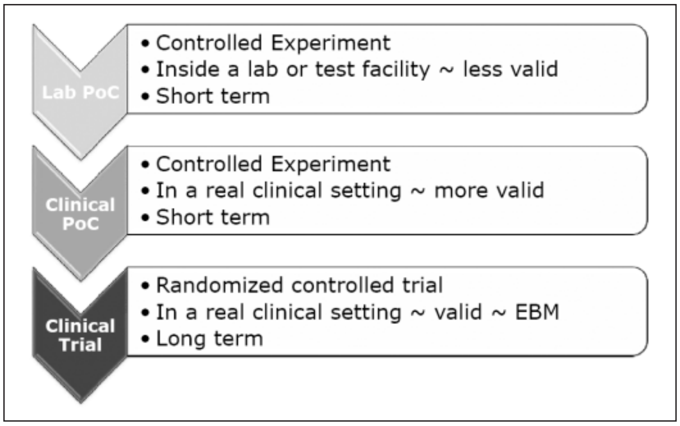

Fig. 4 The timing of a clinical proof-of-concept is between a laboratory proof-of-concept and a full clinical trial.

successful, if it is only tried out by our colleagues in a research laboratory.

From a medical perspective a technical proof-of-concept is clearly not acceptable for introducing new medical technology or treatment. Evidence-based medicine categorizes different types of clinical evidence and ranks them according to the strength of their freedom from the various biases that beset medical research. The strongest evidence for therapeutic interventions is provided by systematic review of randomized, double-blind, placebo-controlled trials involving a homogeneous patient population and medical condition. In contrast, patient testimonials, case reports, and even expert opinion have little value as proof because of the placebo effect, the biases inherent in observation and reporting of cases, and difficulties in ascertaining who is an expert.

Such strong evidence is, however, impossible to obtain while we are still in the research and development phase. So an important question is how we can strike a balance between these two extremes; design and implement technical proof-of-concepts which are suited to provide sufficient clinical evidence for further research and development – to rephrase the definition from Marc Weiser, I would define such a clinical proof-of-concepts as "*the construction of working prototypes of the necessary functionality and infrastructure in sufficient quality to investigate evidence for improving health in daily use for a suitable period of time; a limited but relevant set of people serving as subjects*".

More specifically, the technology should be a working prototype that is usable (but not necessarily user-friendly), works on its own, and is focused on addressing specific research questions. This technology should be deployed in a real clinical environment, should be used by real users (researchers are hands-off), for a short, but sufficient period of time (one day to three months). The methods used during this clinical proof-of-concept should be targeted at collecting evidence, which demonstrate that the technology seems promising in addressing its specific goal. These methods would typically be qualitative in nature, involving observations, questionnaires, studies of perceived usefulness and usability; but may also include more quantitative measures of clinical effect, if possible.

Figure 4 shows the temporal progression of research methods as the technology is developed and mature. Time-wise, a clinical proof-of-concept lies in between the traditional laboratory proof-of-concept and a full-scale clinical trial.

In the two projects described above we did a clinical proof-of-concept (even though we did not call it that at that time). In the home-based blood pressure monitoring project, the technology was deployed for four months having two general practitioners and their hypertension patients involved. This clinical proof-of-concept did not have a sufficiently large number of subjects (nor a control group) to determine if this treatment would improve the patients' blood pressure. The study, however, was sufficiently large to study, understand, and argue that this kind of home-based monitoring would transform the patient-GP relationship and make the patients capable of managing their own blood pressure in a much more efficient way. And since previous clinical studies have shown that regular self-conscious attention to your blood pressure reduces the risk of hypertension, this was clearly a strong indicator that this kind of technology would be useful.

In the interactive hospital project, the AwareMedia and the AwarePhone were deployed in a pilot test for approx. six months at the operating ward of a large Danish hospital. The systems were implemented with sufficient functionality to test our research hypothesis; i.e. the use of context-awareness for coordination purposes, the use of mobile technology, and the use of messaging and video spaces for communication. The prototypes were, however, targeted specifically at this test and there were a number of functional and non-functional features they did not support. For example, only a fixed number of operating rooms (3) were supported, there was no support for configuration, no security, and it was rather monolithic in its nature. On the other hand, the prototypes were robust and could be used by the clinicians without involving the researchers. Again, this clinical proof-of-concept helped us investigate the usefulness of context-aware technologies inside hospitals in general, and for coordinating the execution of operations in particular [9]. Furthermore, using qualitative methods like observations and questionnaires, a majority of the clinicians reported that the systems lead to fewer interruptions, made it easier to locate each other, helped them maintain an overview, made coordination easier, and enabled them to handle changes in the daily operating schedule easier [11]. Hence, this clinical proof-of-concept has provided evidence which indicate that this kind of technology is indeed useful as a new paradigm for computing inside hospitals.

6. Conclusions

Pervasive healthcare is an emerging research field with its own research questions, agenda, approach, and methods. Returning to the questions raised in the introduction, pervasive healthcare addresses the core challenges that most of the OECD countries are facing these years; an increasing elderly population; increasing number of chronic and lifestyle-related diseases, expanding scope of what medicine can do, and increasing lack of medical professionals. The core research question is how new kinds of pervasive computing technologies can be designed and deployed to help us meet these challenges. The short-term impact of this research is the development of better and non-intrusive monitoring systems and personal wellness appliances. On a longer term basis, pervasive healthcare technologies will be part of a fundamental change in the delivery of healthcare services, supplementing the highly centralized and specialized model we have today with a much more decentralized and personal model. Clearly, this will not be achieved just by research into technology – essential issues like health management, organization, and medicine need to be researched too – but technology will be the enabling factor.

A set of core research themes have been outlined including monitoring and body sensor networks; pervasive assistive technologies; pervasive computing for hospitals; and preventive and persuasive technologies. Many more themes exist – such as self-care and self-treatment, therapeutic technologies, decision support systems, and medication support systems – but the space did not allow me to discuss them. I have also provided two prototypical exemplars of research into pervasive healthcare. The first project was targeted at home-based monitoring of hypertension patients, and the second project was designing and deploying context-aware technologies for coordination of work inside a hospital. Both projects could arguably belong to research within telemedicine and medical informatics. But they do not – they are examples of pervasive healthcare research because they approach the challenges in a new way, apply a new type of research method, and come up with new kinds of technological solutions. Clearly, pervasive healthcare is strongly related to its 'sister' research disciplines; biomedical engineering, medical informatics, and ubiquitous computing. But at the same time, pervasive healthcare represents a different approach and focus.

This approach is also reflected in the research methods used within pervasive healthcare, such as the 'clinical proof-of-concept'. Its core idea is to design and construct focused research prototypes to a sufficient functionality and usability to investigate evidence for improving health in daily use for an appropriate period of time, involving a limited but relevant set of people. This method is placing itself – both with regard to timing as well as ambition – between the technical proof-of-concepts made in a research laboratory and the resource-demanding clinical trial.

In this paper, I have used the early cars that were built as a metaphor for pervasive healthcare as a research discipline. At that time it was difficult to see it as anything really new – after all it was just a carriage with an engine instead of a horse, and it did not even run as fast or as reliable as the existing horse-driven ones. Nevertheless, today there is no doubt when we see these early cars; they were the first examples of something really new. What we are experiencing with the different new types of pervasive healthcare technologies is analogue; they do not look as anything new and their performance in solving 'real' medical problems is not as good as the existing approaches. Nevertheless, they are the first examples of a new type of medical technology which will become an important part of solving the challenges of the current healthcare system.

Acknowledgment
This paper has been improved by some very good comments from the reviewers. Some of the questions listed in the introduction are inspired by discussions with Carsten Schürmann, and the use of the picture of a horse carriage with an engine comes from talks with Morten Kyng.

References

1. Bardram JE, Mihailidis A, Wang D, editors. Pervasive Computing in Healthcare. Toronto: CRC Press; 2006.
2. Kaye J, Zitzelberger T. Overview of healthcare, disease, and disability. In [1]; pp 3-20.
3. Dishman E. Inventing wellness systems for aging in place. IEEE Computer 2004; 37 (5): 34-41.
4. Luprano J, Sola J, Dasen S, Koller JM Chetelat O. Combination of Body Sensor Networks and On-Body Signal Processing Algorithms: the practical case of MyHeart project.. In: Proceedings of Body Sensor Network (BSN) 2006 Conference. IEEE 2006; pp 6-79.
5. Choudhury T, Borriello G, Consolvo S, Haehnel D, Harrison B, Hemingway B, Hightower J, Klasnja P, Koscher K, LaMarca A, Lester J, Landay J, Legrand L, Rahimi A, Rea A, Wyatt D. The mobile sensing platform: An embedded system for capturing and recognizing human activities. IEEE Pervasive Computing. 2008; 7 (2).
6. The Polar Homepage. http://www.polar.fi/
7. Rogers MAN, Buchan DA, Small D, Stewart CM, Krenzer BE. Telemedicine improves diagnosis of essential hypertension compared with usual care. Journal of Telemedicine and Telecare 2002; 8: 344-349.
8. Bardram JE, Bossen C, Thomsen A. Designing for transformations in collaboration: A study of the deployment of homecare technology. In: GROUP '05: Proceedings of the 2005 international ACM SIGGROUP Conference on Supporting Group Work. 2005. pp 294-303.
9. Bardram JE, Hansen TR, Soegaard M. AwareMedia: a shared interactive display supporting social, temporal, and spatial awareness in surgery. In: CSCW '06: Proceedings of the 2006 conference on Computer supported cooperative work. 2006. pp 109-118.
10. Weiser M. Some Computer Science Issues in Ubiquitous Computing. Communications of the ACM 1993; 36 (7).
11. Hansen TR, Bardram JE. Applying Mobile and Pervasive Computer Technology to Enhance Coordination of Work in a Surgical Ward. In: Proceedings of the 2007 MedInfo Congress 2007. pp 373-376.

Correspondence to:
Jakob E. Bardram
IT University of Copenhagen
Rued Langgaards Vej 7
2300 København S
Denmark
E-mail: bardram@itu.dk