Towards a Medical Tricorder:
Defining medical conditions for consumer self-care with focus on non-invasive technologies

Full Papers

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Abstract
Health and fitness applications, fitness trackers and wearables show particularly high, sustained demand among private consumers. Highly efficient and cost-effective digital consumer electronic sensor technologies can also be used for medical purposes. Non-invasive technologies offer capabilities in the detection, measurement, and analysis of medical conditions carried out by private consumers. This paper investigates the technological readiness of consumer electronics for the measurement of vital signs, cardiovascular / metabolic and infectious diseases and shows how these technologies can promote self-care of consumers. We propose a 3-dimensional framework which characterizes diseases according to their burden of disease, their potential for self-care and the readiness of enabling technologies in consumer devices. With the evaluation of current technologies we show that a growing number of medical conditions, especially lifestyle-related cardiovascular diseases, can be identified and monitored easily, precisely and non-invasively by consumers. Consumer electronic technologies can no longer be seen only as a complementary element besides professional medical procedures but are increasingly able to provide medical diagnoses and monitor diseases without medical examination. Based on a 3D-self-care framework we propose strategies for three target groups: Consumers should focus on lifestyle-related diseases, healthcare payers should focus on research funding for technologies addressing high burden diseases and technology developers should focus on diseases that can be supported by close-to-market technology.

Keywords
Self-care, sensors, consumer, healthcare, technology

Introduction
The increase in so called “civilization diseases” has been recorded in industrialized countries such as Germany for many years (Robert Koch-Institut 2015). Lifestyle-related cardiovascular diseases and metabolic disorders, such as diabetes, are rapidly growing problems (World Health Organization 2016a). At the same time, self-care is increasing as well. The WHO defines self-care as „[…] the ability of individuals
...to promote health, prevent disease, and maintain health and to cope with illness and disability with or without the support of a health-care provider” (World Health Organization 2009, p. 17). The raising awareness of self-care is reflected in a growing sales volume of fitness applications for smartphones and fitness trackers in the field of consumer electronics. The core objective of these is to track and monitor vital parameters mainly for sports-related reasons (GFK SE 2016). A continuously increasing measuring accuracy and technical performance also raises the attractiveness of non-invasive mobile technologies for the medical sector. The impact of mobile consumer technology on healthcare providers and healthcare systems can be leveraged, if the development of future technology is guided by the need to support the most common and relevant self-care aspects.

Accordingly, innovations in mobile health technologies and medical tricorders for the consumer electronics area are supported. Particular commitment is shown by Qualcomm’s XPRIZE. The prize was announced in 2013 by the XPRIZE foundation and is endowed with USD 10,000,000. The aim of this prize is to develop a medical tricorder which will be able to detect a preselected set of vital signs and diseases non-invasively (XChallenge 2014; XPrize 2016). Mobile technologies are increasingly used in the consumer electronics area and for applications in the medical sector. This gives rise to new business models and possible actions for consumer self-care, which is no longer totally reliant on professionals and medical instruments. Therefore, it should be possible for consumers to use these technologies independently, to promote self-care. The scope lies on accessible and easy to use technologies which are open to the public and are already on the market or will be available in the near future.

The central focus of this paper is to select and evaluate non-invasive technologies and their abilities to increase health literacy and consumer self-care. Next, this study examines how measurement of vital signs and diseases may help to promote self-care and which implications can be derived for consumers, health insurance funds and technology manufacturers. The goal is to evaluate suitable, non-invasive technologies for the measurement of medical conditions and to examine how these technologies may improve consumer self-care, especially in the field of lifestyle-related diseases.

**Methodology**

We based the research on theoretical medical background knowledge of selected conditions in a literature review. This literature reviews medical diseases and outlines current knowledge about the selected vital signs and diseases (Herold 2010; Piper 2013; Prinz and Ott 2012). The dimensions of the 3D-self-care framework are developed as follows.

The burden of disease is determined for each condition with the aid of quantitative epidemiological data such as incidence and prevalence rates. These serve as a benchmark for the classification of the burden of disease (Department of Health New York State 1999; Pai and Filion 2003). The results are classified into three categories and graphically displayed as the dimension “burden of disease”. Second, we characterize conditions into one out of three bubble sizes, according to their self-care relevance. The influence of lifestyle factors correlates directly with the relevance of self-care to consumers and thus the size of the bubble. The more influential lifestyle factors are for a disease, the more relevant self-care is to consumers and the bigger the bubble will be. “Self-care relevance” therefore determines the second dimension. The third dimension deals with technical feasibility. The obtained products and solutions are presented and their underlying technology is explained. Each medical condition is sorted into one of the three categories: early stage, medical and consumer electronics, depending on the technological readiness for the measurement of the medical conditions.

The framework merges key findings in a three dimensional chart. We describe the results of the graphical model, discuss major insights and derive implications for our interest groups. Subsequently, we critically reflect the methodology and answer the research questions. Finally, further perspectives for research and practice will be provided.

**Dimensions**

In the following section, the relevant theoretical foundations which are necessary to understand and implement the categorization of our framework will be described. Therefore, we describe the three dimension of the self-care framework.
**Conditions**

We inspect vital signs and diseases which are substantially aligned with the medical conditions mentioned at Qualcomm’s XPRIZE (XPRIZE Foundation 2012).

First, selected vital signs that are usually assessed during medical inspections are measured to get a quick overview of the physical health of a patient. Five essential vital signs and their detection are taken into account. In the second step 19 diseases are identified, along with their epidemiology, international ICD-categorization, as well as causes and measurement methods for the detection of these diseases. Finally, the burden of disease for each condition is determined on the basis of their respective epidemiology. Primary vital signs are permanently defined and include the parameters of body temperature, blood pressure, heart and pulse rate and respiratory rate (Fetterman and Kang n.d.). Additionally, oxygen saturation will be addressed as a fifth vital sign. Diseases are grouped into two major categories – cardiovascular/metabolic diseases and infectious diseases. Within this work, metabolic and cardiovascular diseases are merged into one category since they often appear jointly together and affect each other strongly.

Every disease is defined and classified by the International Statistical Classification of Diseases and Related Health Problems (ICD-10). Following this classification, the epidemiology will be determined for each disease. This is necessary for the determination of the burden of disease. For this study, the burden of disease indicates one person’s probability for developing a disease within a certain period of time or of having a disease at a specific point in time. It is not to be confused with the Global Burden of Disease, which evaluates mortality and disability caused by major diseases and injuries and which has been used by several organizations, such as the WHO or Harvard School of Public Health since 1990 (World Health Organization n.d.). In order to be able to determine the corresponding burden of disease for each condition, three categories are defined. Each category is characterized by its epidemiological thresholds for incidence, prevalence, and lifetime prevalence/total prevalence. Thus, each disease can be sorted into one category based on their incidence or prevalence rate (WHO, 2016), resulting in a low (< 2%), medium (2 – 9 %) or high (> 9 %) burden of disease. After categorizing all diseases on the basis of their epidemiology and applying the criteria mentioned above, the burden of disease for each condition can be displayed (cf. Figure 1).

![Figure 1: Burden of disease dimension](image)

On the X-axis, diseases are sorted according to their burden of disease in ascending order. On the left, there are diseases with a low burden of disease, while on the right, there are conditions which were categorized as conditions with a high burden of disease. The low and medium burden of disease category are each represented by four diseases. While the burden of disease might be low for some conditions, correct and prompt treatment for these diseases (HIV, pertussis, malignant melanoma) still is essential and a lack of treatment may even lead to death (AIDS.gov 2015; Sandru et al. 2014).

More than half of the examined diseases (57.9%) show a high burden of disease. This includes both cardiovascular/metabolic diseases and infectious diseases, which tend to have high prevalence and incidence rates. This especially includes diabetes mellitus, hypertension and high cholesterol which are all components of metabolic syndrome. In addition, diabetes and hypertension are also main risk factors of COPD, which once again favors chronic pharyngitis. This confirms the statement, claiming that cardiovascular and metabolic diseases often occur and manifest together and tend to be accompanying illnesses, or secondary diseases of each other. After we categorized and determined the burden of disease for each condition, the impact of lifestyle-related causes and risk factors for the development of diseases is examined.
Self-Care

Self-care relevance describes the extent to which a certain medical condition is influenced by lifestyle-related causes and factors and the influence consumers have on this condition. Accordingly, a low self-care relevance indicates that a disease is not or only to a small extend induced by lifestyle and lifestyle-related factors of individual consumers. On the other hand, a high self-care relevance implies that a disease is highly or predominantly induced or even caused by lifestyle and lifestyle-related factors of individual consumers. The term has been chosen to point out which diseases are impacted by consumers. In other words, diseases with a high self-care relevance can be positively influenced by lifestyle changes made by consumers themselves without the need of medical institutions, while diseases with a lower self-care relevance may be the result of other non-lifestyle related causes. This interpretation of self-care focuses on preventable condition and less on the self-care aspects during treatment. The aim of self-care relevance is twofold. On the one hand, the impact of lifestyle-related factors on diseases are examined. On the other hand, it is outlined which disease condition may improve or even heal due to lifestyle changes of the consumer. Two assumptions are made:

1. Consumers are in a position to make conscious changes in lifestyle
2. High and medium self-care relevant diseases are positively affected by specific changes of lifestyle

Self-care relevance for each disease is determined by evaluating medical literature and studies. Based on the description of diseases, we examine known causes and risk factors. A distinction is made between lifestyle-related and non-lifestyle related causes and risk factors to determine the self-care relevance later. Due to reasons of complexity, correlations and interdependencies of causes and risk factors are not taken into account. For this paper, lifestyle-related causes and risk factors are subdivided into four areas (cf. Figure 2).

![Figure 2: Lifestyle related causes and risk factors](image)

Other factors, which are not listed above are counted as non-invasive-lifestyle related causes and risk factors. Occupational risks (increased risk of infections for doctors and staff working for healthcare institutions, sun exposure of construction workers, etc.) are not considered as lifestyle-related causes and risk factors.

Next, every condition is assigned to a degree of self-care relevance. Diseases which have been detected as being weakly related to a consumer’s lifestyle, receive a low self-care relevance, respectively partially lifestyle-related diseases are marked with a medium-self-care relevance. Diseases which have been detected as predominantly lifestyle-related receive a high self-care relevance. The circle size represents the self-care relevance of each condition. Our results show that five out of six predominantly lifestyle-related diseases are cardiovascular/metabolic diseases (COPD, diabetes mellitus (type II), high cholesterol, hypertension, sleep apnea). Moreover, they share mainly the same causes and risk factors. Especially diabetes mellitus, hypertension and high cholesterol are closely linked with each other and are frequently accompanying, co-exist or are secondary diseases.

The categorization of diseases is used for the determination of the self-care relevance for each disease. The goal of the self-care relevance dimension is to visualize all diseases and to set them in relation to their lifestyle-related causes and risk factors in order to determine which diseases can be influenced by consumers. The self-care relevance for each disease is symbolized by the circle size of the condition (cf. Figure 3). Furthermore, conditions are sorted in ascending order starting with a low burden of disease and growing rightwards.
Figure 3: Self-care relevance dimension

The evaluation of results shows that non-lifestyle-related causes and risk factors for cardiovascular diseases are mainly advancing age and familial dispositions (heredity). On the other hand, the main lifestyle-related causes and risk factors for cardiovascular diseases are high calorie, poor diets with highly saturated fats and sugar intake, drug consumption, mainly represented by alcohol and tobacco use, as well as physical inactivity.

Regardless of the burden of disease the large majority of cardiovascular and metabolic diseases fall into the high self-care category. Five out of six diseases which are located in the high self-care category are cardiovascular and metabolic diseases. Diabetes mellitus, hypertension, high cholesterol and COPD are predominantly lifestyle-related and both show a high burden of disease and a high self-care relevance. For this reason, in the technology evaluation we select these four cardiovascular and metabolic diseases.

Technologies

For this study, “technology” refers to both software and hardware which is capable of detecting and measuring medical conditions in consumers. For the purpose of simplification, throughout this paper technology covers all approaches, concepts, prototypes, products, sensors and devices dealing with non-invasive technologies for the measurement of medical conditions. In addition, detected technologies need to be sufficiently precise, easy to use and accessible for consumers in order to enhance individual self-care.

Sufficiently precise means that a technology is able to reliably identify and measure individual or multiple medical conditions. This can be ensured through governmental and independent institutions which certify devices. In particular, this includes the CE marking for medical devices within the European Union, ISO standards, and FDA cleared or FDA-approved devices. In order to receive one of these certificates, devices not only have to pass a harmlessness test, but also need to fulfill capability tests, environmental compatibility and meet additional quality requirements (Kirsch 2015; U.S. Food and Drug Administration 2009, 2015a, 2015b).

At first, we search for technologies for respective medical conditions using specified keywords. In a second step, the results are aggregated and structured by sorting out duplicate reports, failed and outdated technology concepts and unproven claims of online sources. Following this, the detected technologies and products are filtered. Products, which were available on the market before 2005 or which use invasive measurement methods are sorted out. If there is more than one product using the same technology, one manufacturer is selected representatively. The third step involves the explanation of the underlying principles and technologies of the products and devices being studied. Finally, the technical feasibility of each medical condition is determined.

Overall, 255 websites, conferences1, societies2, medical and technology blogs3, online journals and commercial sites were studied using the following keywords in combination with each medical condition:

2 http://www.ismit.org/, https://medtechboston.medstro.com/
After aggregating and summarizing the results, 181 technology approaches, prototypes, scientific studies, products, sensors, and devices were detected. 85 of them were selected after filtering.

The technical feasibility is divided into three categories: early stage, medical devices, and consumer electronics. The classification is based on the criteria precision, ease of use, and availability. In the sector early stage we identify medical conditions which either cannot be measured with non-invasive technologies or where only prototypes are available. Depending on the approach and technology, it has not been sufficiently demonstrated that a medical condition can be measured repeatedly and precisely (lack of precision), they are not user-friendly (lack of ease of use) and are not available on the consumer electronics market (lack of availability). The early stage category equates to a low technical feasibility.

In the medical device sector technologies for the precise, non-invasive measurement of medical conditions exist, which are used in medical facilities (precision). Technologies in this section often need to be operated by professionals (lack of ease of use) and are not available as consumer electronics (lack of availability). The medical device category represents a medium technical feasibility.

Technologies for medical conditions in the consumer electronics category fulfill all three criteria. These technologies are proven to be precise in measurement (precision), simple to use by private consumers (ease of use) and available for private purposes (availability). Medical conditions in this category are assessed with a high level of technical feasibility.

![Figure 4: Technical feasibility dimension](image)

The graph shows each of the examined diseases by their technical feasibility. The vertical Y-axis represents the technical feasibility for each disease and is divided into the three sectors: early stage, medical, and consumer electronics. Each disease is categorized according to its technical feasibility in ascending order. The higher a disease is listed, the higher its level of technical feasibility.

An even distribution of the examined technologies for each disease onto the early stage sector (7 diseases), the medical sector (5 diseases), and the consumer electronics sector (7 diseases) can be seen. For almost any medical condition (including vital signs) at least early stage approaches or research is conducted. However, there are big differences between detection and monitoring of vital signs, cardiovascular/metabolic diseases and infectious diseases. Devices for the measurement of vital signs are

**Keywords:** non-invasive, minimally invasive, consumer electronics, prototype, detection, diagnostic, measurement, monitoring, analysis, innovation, health device, technology, wearable, wearable technology, medical wearable, sensor, tracker, wristband, lenses, tech-tat, medical patch, biotech-tattoo
not only the most advanced and all located in the consumer electronics sector, but are often able to monitor multiple vital signs simultaneously.

The majority (5/8) of the technologies for cardiovascular/metabolic disease detection and measurement has reached the consumer electronics sector. Early stage technologies are almost exclusively occupied by infectious diseases. Apart from HIV detection, no other technology for infectious disease measurement is in the consumer electronics sector. Reasons for this might be that infections are more difficult to detect than cardiovascular/metabolic diseases due to lack of precision resulting from low sensitivity or specificity and possible impurities of samples.

Some of the devices which are ranked as a consumer electronics device still might need known medical procedures or medical staff for evaluations. For example, the App for malignant melanoma detection or a simple HIV test will need additional professional tests after a positive result. The same applies to minimally invasive measurement methods like the FreeStyle Libre device which still needs a small needle in order to deliver results which are precise enough (Smith 2015).

3D-Self-Care Framework

In this section we graphically present the main results of previous sections, discuss the outcomes of this study and derive practical recommendations for our interest groups. The 3D self-care framework combines the burden of disease, self-care relevance, and technical feasibility of each disease within a single graph.

Figure 5: 3D self-care framework

The X-axis of the 3D self-care framework is divided into three areas: low, medium and high, and shows the burden of disease ascending, from the left to the right. The burden of disease measures one person’s probability for developing a disease within a certain period of time or of having a disease at a specific point in time. The positioning of the disease on the X-axis is correlated with the level of burden of disease.

The Y-axis indicates the technical feasibility, rising from bottom to top and categorized into three sectors: early stage, medical and consumer electronics. The technical feasibility indicates how well a medical condition can be measured by private consumers, through non-invasive technologies. Each disease is represented by a circle. The circle size provides insights into the self-care relevance of a disease. Self-care
relevance describes the extent to which a certain medical condition is influenced by lifestyle-related causes and factors and the influence consumers have on this condition.

A high burden of disease is detected in 11 out of 19 diseases, equally distributed among cardiovascular/metabolic and infectious diseases. Major differences can be seen in terms of self-care relevance. Infectious diseases are hardly associated with lifestyle related factors, mainly resulting in low self-care relevance (6/10 diseases) and medium self-care relevance (3/10 diseases). Lifestyle-related causes and risk factors of infectious diseases and malignant melanoma are mainly attributed to preventive actions not considered in this study. This includes primarily unprotected intercourse (HIV), irregular vaccinations (pertussis), and intense sun exposure (malignant melanoma).

In contrast, cardiovascular/metabolic diseases are predominantly lifestyle-related (5/8 diseases). 5 out of 6 diseases with a high self-care relevance are cardiovascular/metabolic diseases. Lifestyle-related causes and risk factors of these diseases are: diet/nutrition (high calories, sugar, saturated fats), drug consumption (tobacco, alcohol) and physical inactivity. This applies in particular to comorbidities of the metabolic syndrome such as diabetes type II, hypertension and high cholesterol as well as COPD (Geldmacher et al. 2008). Vital signs, technical feasibility, and technologies for detection and measurement of vital signs are consistently high and are established in the consumer electronics sector. A growing number of specific technologies are able to detect and monitor multiple vital signs and diseases such as atrial fibrillation at once.

The technical feasibility of the examined diseases is distributed evenly across the early stage, medical, and consumer electronics sector (7/5/7 diseases). Aside from HIV, which has reached the consumer electronics sector, infectious diseases are mainly located in the early stage sector or at the lower end of the medical sector (7/10 diseases). Cardiovascular/metabolic diseases, on the other hand, are represented mainly in the consumer electronics sector (5/8 diseases) and show a high technical feasibility. Currently for most of the examined medical conditions, there are early stage concepts and technologies which aim at the consumer electronics market and are planned for completion within the next three years.

Increasing precision in the field of detection and measurement of medical conditions, ease of use for consumers and availability of technologies in consumer electronics steadily raise the technical feasibility. Consequently, increased technical feasibility entails growing self-care in consumers.

**Discussion**

**Implications**

At this stage, implications are mainly addressing the field of practice. Based on our results, the following recommendations for consumers, health insurance funds, and technology manufacturers are derived:

**Consumers**

Consumers should initially focus on their existing diseases which are categorized with a high self-care relevance such as diabetes type II, hypertension, high cholesterol, and COPD. Since these diseases are closely lifestyle-related, consumers themselves can have a major impact by implementing simple lifestyle changes. The focus should lie on minimizing lifestyle-related causes and risk factors by optimizing diet and nutrition, discouraging drug consumption and enhancing physical activity. Consumers should then aim to prevent diseases with high and medium self-care relevance. Cardiovascular/metabolic diseases can be prevented by proper diet and nutrition, reduced drug consumption, and regular physical activity. Infectious diseases can be prevented by vaccinations (pertussis) or safe sex (HIV). The risk of malignant melanoma can be reduced by the avoidance of long periods of intense sun exposure.

**Health insurance funds**

Health insurance funds should address diseases with a combined high self-care relevance and high burden of disease as those cause avoidable high costs. Through further development of relevant technologies and promotion of health literacy among customers, expenditures can be reduced. Next, health insurance funds should deal with diseases with high and medium self-care relevance, due to high and long follow-up costs (HIV, malignant melanoma). Investing in technologies for the detection of these diseases and the preventive education of their customers can help to prevent diseases. Furthermore, health insurance funds are advised to deal with diseases with a high burden of disease since significant parts of their customers are affected.
Technologies for quick and reliable detection of those diseases do not only save time and costs for expensive laboratory tests (infections) but also enable more efficient treatments of patients.

Technology manufacturers

Technology manufacturers should implement a market penetration strategy for diseases which have reached a high technical feasibility because the related technologies are already available for consumers and cause only minor further development expenses. They are encouraged to invest in technologies which detect and monitor diseases with a high burden of disease. Consumer and medical demand is correspondingly large and potentially competitive. Pioneer advantages can thereby be realized with early stage and medical technologies.

Limitations

This study mainly focuses on the aspect of technical feasibility of non-invasive measurement of medical conditions and how medical diseases can be detected and measured without the support of a health-care provider. The assumption was made that an increased feasibility directly resonates with an enhanced understanding of self-care by consumers. However, technological enablement itself is only one part which defines self-care and should be complemented with actions to raise awareness and specific recommendations for consumers. Measurement alone cannot increase self-care of individuals without further actions or lifestyle changes to promote and maintain health, and prevent disease.

Future research

This study shows that non-invasive technologies are not only capable of monitoring medical conditions but that they will also help to prevent diseases through early detection in the near future. They will no longer be restricted to the measurement of medical conditions but start searching for possible causes, making diagnoses and giving practical advice based on the measurement results. Particularly patients with reduced mobility or people living in areas with little medical infrastructure can benefit from those developments.

In this regard, it has to be examined how proper diagnosis and suitable recommendations can be made on the basis of measurement results and how accurate these diagnoses are. Furthermore, the potential benefits and fields of application of these technologies for hospitals and medical staff should be evaluated. Future research should also focus on subsequent development of technologies for the detection of infectious diseases. Developing countries with insufficient health services would benefit most from an extensive, fast and cost-efficient detection of infectious diseases. In addition, regulations for security and privacy of patient data and exchange of sensible data content between devices and clouds needs further discussion.

REFERENCES


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