Medical Virtual Instrumentation for Personalized Health Monitoring: A Systematic Review

Olufemi Adeluyi and Jeong-A Lee
Department of Computer Engineering, Chosun University, Seosok Dong, Gwangju, Korea

Submitted March 2015. Accepted for publication July 2015.

ABSTRACT
The rising cost of healthcare and the increased senior population are some reasons for the growing adoption of the Personalized Health Monitoring (PHM) systems. Medical Virtual Instruments (MVIs) provide portable, flexible, and low-cost options for these systems. Our systematic literature search covered the Cochrane Library, Web of Science, and MEDLINE databases, resulting in 915 articles, and 25 of which were selected for inclusion after a detailed screening process that involved five stages. The review sought to understand the key aspects regarding the use of MVIs for PHM, and we identified the main disease domains, sensors, platforms, algorithms, and communication protocols for such systems. We also identified the key challenges affecting the level of integration of MVIs into the global healthcare framework. The review shows that MVIs provide a good opportunity for the development of low cost personalized health systems that meet the unique instrumentation requirements for a given medical domain.

Keywords: personalized health monitoring, medical instrumentation, telemetry, electrocardiogram (ECG), electroencephalography (EEG)

1. INTRODUCTION
Personalized Health Monitoring (PHM) refers to long term monitoring that is performed by a novice patient in an uncontrolled environment, such as his/her home [1]. It is a veritable tool that supports not only the monitoring of a patient's health status, but also the transition from a hospital-based, physician-centered healthcare delivery system, to one that is home-based and patient-centered. This transition has become necessary in the wake of challenges such as rising healthcare costs, dwindling healthcare budgets, a growing proportion of senior citizens in developed societies, and a growing need for medical systems personalized to suit the user specific needs [2, 3, 4].

The feasibility and effectiveness of PHM depends on the availability of a pragmatic approach for providing medical instruments at the patient's home, similar to the traditional instruments found at a hospital. Unfortunately, many of these instruments are expensive

*Corresponding author: Jeong-A Lee, Department of Computer Engineering, Chosun University, 375 Seosuk-Dong, Dong-Gu, Gwangju, 501-759, Korea. Phone: +82622307711. Fax: +82622307755. E-mail: jalee@chosun.ac.kr. Other author:adeluyi@chosun.kr.

and inconveniently bulky, and providing them at the patient's home would nullify a number of potential benefits of PHM, including its low cost and portability. Virtual instruments can provide these tools to patients without forgoing the benefits of PHM.

A virtual instrument is an instrument that utilizes a hardware-software approach to system implementation. It takes advantage of the high performance of hardware and high flexibility of software to greatly reduce the size of the corresponding traditional instrument without sacrificing much of its functionality [5,6]. The hardware portion comprises the sensor, display, and memory, while the software part is made up of the processing and interface modules. These instruments can be deployed in several contexts and their specific use essentially depends on the creativity of the designer [7]. Medical Virtual Instruments (MVIs) are virtual instruments that are used within the context of medicine. They approach home-based health monitoring in a way that emphasizes system re-use, modularity, adaptability, and user-defined instrumentation. For this review, we are interested in MVIs that are used for PHM. These systems are expected to monitor patients' health and support medical tests in key domains of medicine [8–10].

The objective of this systematic review is to give an overview of the current body of work covering the use of virtual instruments for personalized health monitoring. The emphasis is on the identification of key architectures used for MVIs in terms of the type of sensors, architecture, modality, communication interface, and network model. Second, it describes the important application domains of MVI, its level of adaptation, and the common algorithms utilized. Third, it outlines the key outcomes of using MVIs for PHM as well as the current challenges and the anticipated future research direction for the field.

The remainder of this review is organized as follows:In Section 2, we present the Materials and Methods used to carry out the review. In Section 3, we outline the Results of the most common features of PHM-based medical instruments. We then discuss the results in Section 4, and conclude in Section 5.

2. MATERIALS AND METHODS

2.1. Search Strategy

A systematic literature search was performed to identify studies on MVI using the following databases: MEDLINE (1996–August 2014), Web of Science (1973–August 2014) and Cochrane Library (1992–August 2014). The relevant fields and research areas were identified and the following search query was used without limitations on the year or type of publication:

For MEDLINE:

Query: ("user-computer interface"[MeSH Terms] OR ("user-computer"[All Fields] AND "interface"[All Fields]) OR "user-computer interface"[All Fields] OR ("virtual"[All Fields] AND "systems"[All Fields]) OR "virtual systems"[All Fields]) AND ("instrumentation"[Subheading] OR "instrumentation"[All Fields]) OR ("equipment and supplies"[MeSH Terms] OR ("equipment"[All Fields] AND "supplies"[All Fields]) OR "equipment and supplies"[All Fields] OR "device"[All Fields]) AND ("telemedicine"[MeSH Terms] OR "telemedicine"[All Fields]) AND Monitoring[All Fields].

For Web of Science and Cochrane Library:

Query: ("Virtual Systems" AND "Instrumentation" OR "Device" AND "Telemedicine" AND "Monitoring").

The search resulted in 915 articles, with 642 from MEDLINE, 233 from Web of Science, and 40 from the Cochrane Library.

2.1.1. Selection Process

Our selection process was based on the following 5-stage strategy:

i. Deletion of doubles
ii. Title scan
iii. Abstract scan
iv. Cursory full text scan
v. Detailed full text scan

We started by deleting the 46 articles that were duplicated before a screening based on their titles. Titles that indicated contents different from research related to PHM and MVI were discarded. There were 573 articles discarded at this stage, leaving a total of 296 articles for the abstract-scan stage. During the abstract scan, we eliminated articles that did not align with the theme of our review, and 127 articles were filtered out at this stage.

The remaining 169 articles were subjected to a cursory scan of the full text, which essentially involved identifying the sections, as well as reading the introduction, discussion, and conclusion sections. Articles that did not give sufficient details on the items listed in our objectives were discarded. After this stage, there were 56 articles that were subjected to a detailed full text scan, and 39 of which were discarded. The criteria included those listed in the previous stage. A preference was also given to articles that covered multiple domains, those that addressed unique applications, and those that described the instrumentation process in some detail. After all these stages, we had 25 articles that were included in this review. A description of each of these articles is given in Appendix A. The search strategy is shown in Figure 1.

3. RESULTS

Based on the analysis of the 25 research articles included in this review, we identified a number of key features that characterize the use of MVIs for PHM. These features will be discussed in the subsequent subsections as follows:

- Architecture
- Application
- Outcomes

3.1. Architecture of MVIs

The architecture describes the hardware portion of the MVI and the communication interface. It comprises the sensors, system platform, and the communication interface utilized for both the local and remote ends of the MVI.

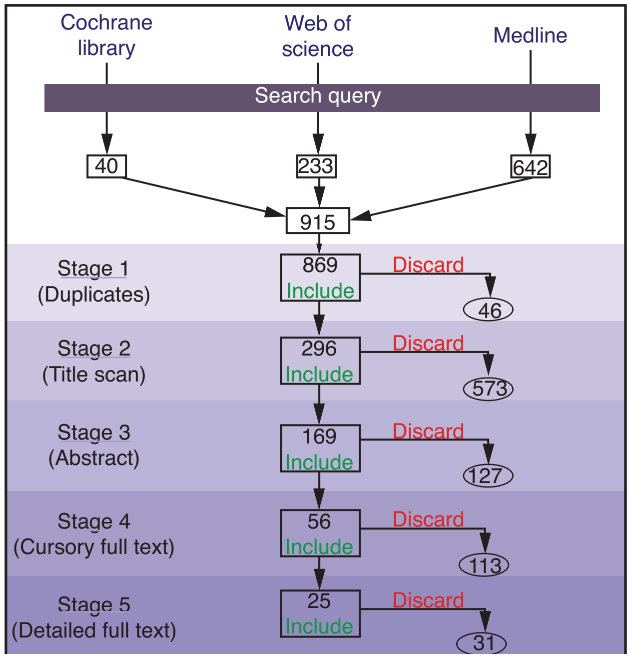

Figure 1. Search strategy.

3.1.1. Sensors and Sensing

The sensors capture the analog bio-signals from the patient and condition them for further processing. Table 1 shows the parameters and types of sensors used in the selected articles and the percentage of the 25 studies where they were used.

At 40.0%, Electrocardiogram (ECG) sensors represent the most extensively used sensors for MVIs. As shown, when the Cardiac Implantable Electronic Device (CIED) sensors are included, the percentage rises to 48.0%, implying that close to half of MVI systems monitor heart signals. Blood pressure (BP) sensors and accelerometers are next in prevalence at 24.0% each. It is interesting to note that a number of these sensors measure signals as a proxy for another signal of interest and are thus known as virtual sensors.

Virtual sensors [17,18] are quickly becoming an important part of the MVI architecture. They refer to sensors that are based on software rather than hardware and they infer their readings from the relevant hardware sensor(s). These virtual sensors enable patients to monitor bio-signals for which it is either impractical to have access to the signal of interest or for which the sensors or related equipment may be too expensive. From the reviewed articles, there were 12 cases, or 48.0%, that used virtual sensing. The actual sensors used for this process are listed in Table 2.

Table 1. Sensors and parameters measured in MVIs

S/No.	Sensor	Cases	%
1	Electrocardiogram [11, 14, 20, 21, 22, 23, 24, 27, 30, 31]	10	40.0
2	Blood pressure [11, 14, 21, 25, 27, 29]	6	24.0
3	Accelerometer [14, 22, 26, 27, 29, 32]	6	24.0
4	Oxygen saturation [14, 21, 27, 29]	4	16.0
5	Temperature [14, 25, 29, 30]	4	16.0
6	Microphone [15, 28, 30, 37]	4	16.0
7	Posture [14, 21, 29]	3	12.0
8	Pressure [16, 25, 35]	3	12.0
9	Weight [11,21]	2	8.0
10	Cardiac implantable electronic device [12,19]	2	8.0
11	Gyroscope [14,32]	2	8.0
12	Blood glucose [33,36]	2	8.0
13	Photodiode [29]	1	4.0
14	Surface electromyography [13]	1	4.0
15	Electroencephalography [34]	1	4.0
16	Tilt [22]	1	4.0
17	Camera [30]	1	4.0
18	Pedometer [32]	1	3.8
19	Gastrocnemius expansion [32]	1	3.8
21	Electro dermal activity [37]	1	3.8
22	Chest impedance [21]	1	3.8

Table 2. Examples of inferred parameters in MVIs

S/No.	Inferred Parameters	Actual Sensor	No of Cases
1	Respiratory rate [14, 26 29, 35]	ECG, accelerometer, pressure	4
2	Heart rate [29,31]	ECG	2
3	Respiratory input impedance [16]	Pressure	1
4	Drowsiness [37]	Electro dermal activity (EDA)	1
5	Gait analysis [32]	Gastrocnemius expansion Measurement unit (GEMU)	1
6	Parkinson's disease Progression [15]	Microphone	1
7	Obstructive sleep apnea syndrome (OSAS) [28]	Microphone	1
8	Consciousness awareness [34]	EEG	1
	Total		**12**

3.1.2. Platform

Virtual instrumentation was introduced to the consumer market in the late 1980s by a company known as National Instruments through a product called LabVIEW (Laboratory Virtual Instrument Engineering Workbench). Other products currently available in the virtual instrumentation space include the Simulink software from Mathworks and the BioMobius [38] open source biomedical platform developed by the Technology Center for Independent Living (TRIL), Ireland. The Reconfigurable Virtual Instrumentation (RVI) open source platform of the International Center for Theoretical Physics (ICTP) in Trieste, Italy is another similar platform. It uses a Field Programmable Gate Array (FPGA) as its reconfiguration engine [39] and has been used to develop a neural monitoring system. Essentially, most of these virtual instruments are required to run on a dedicated general-purpose computer.

MVIs are developed to support PHM systems for which portability is an important requirement. Unlike the general virtual instrument approach, most MVIs do not use a PC as their platform, but instead a custom device [14–16, 20–23, 25–29, 32, 33–37] or a mobile phone/personal digital assistant (PDA), [11, 13, 24, 30, 31, 33] as shown in Table 3. The two cases of Cardiac Implantable Electronic Devices (CIEDs) [12,19] were not included since they only use mobile phones for communicating with a remote system.

3.1.3. Network Models and Communication System

All of the MVIs in the reviewed articles were based on a client-server network model. In most systems, the sensed signals were forwarded from the local (patient) end to an access point device in close proximity to the sensors for onward transmission to a remote server at the remote (physician) end. In many cases, the platforms described in the previous section are used as the access points.

One trend worth noting about MVI network models involves the direct connection between the output of the bio-signals and a remote webserver or cloud service, rather than a connection to a specific remote server on the physician's end. Five of the reviewed articles [22, 28, 31, 36, 37] used such a model. A number of advantages can be derived from this approach. One such advantage is the potential of "geographically decoupling" the bio-signals [36]. In other words, it reduces the mobility restrictions on

Table 3. Platforms and protocols used in MVIs

Platforms			
	Custom Devices	PDA/Phone	Laptop/PC
Cases	17	6	1
Local-MVI Communication Protocols			
	Wireless	RS-232	Others
Cases	17	2	3
Remote MVI Communication Protocols			
	Cellular	WiFi	DSL
Cases	14	9	2

the patients since their signals can be streamed to the webserver while they move about freely. Another advantage is that many different authorized personnel, such as the physician and the caregiver, can simultaneously view the patient's signals. The approach can also exploit the memory and processing capabilities of a web or cloud service while reducing the computational complexity of the MVI at the patient's end.

Communication via MVIs can either occur within the local patient modules or between the physician's remote MVI and the patient's local MVI. The communication in the former is known as local-MVI communication, while the latter is known as remote-MVI communication. The remote MVI is similar to the local MVI, with exception to the inclusion of the remote's bio-signal sensors. Much of its functionality involves the analysis of the signals, which results in a greater storage and processing capacity in the remote MVI.

The wireless protocol was the most common for local-MVI communication and was used in 73.9% of the cases (Table 3). This included 26.1% for Bluetooth [11, 21, 30, 31, 33, 34], 8.7% for ZigBee [22,24], and 39.1% for unspecified wireless protocols [12, 19, 20, 23, 25, 28, 29, 32, 33]. RS-232 protocols were used in 8.7% of the cases [14,37] and another 17.4% used other methods [15, 16, 20, 36]. Some articles did not specify the local-MVI communication protocol [26, 27, 35].

The cellular networks were the most common approach for intra-MVI communication, used in 56% of the cases [11–14, 19–21, 24, 27–30, 33, 36]. It was followed by the wireless approach at 36%, 28% of which were with Wi-Fi [13, 16, 20, 22, 24, 31, 32] and the remaining 8% with unspecified wireless techniques [16,23]. DSL techniques were used in 8% of the references [16,21]. The details are shown in Table 3. Some articles used multiple techniques for remote-MVI communication while others failed to specify the local-MVI communication protocol [17, 25, 26, 27, 34, 35, 37].

3.2. MVI Applications

MVI applications refer to the disease domains, adopted modality, level of system adaptability, and algorithms that govern the operation of the instrument.

3.2.1. Disease Domains

MVIs can be used for, but are not limited to medical research applications, clinical applications, medical design development, healthcare information management systems, and mathematical modeling of physiologic systems [7]. However, from the analysis of the research articles in this review, we found that the use of MVIs for PHM focuses on certain specific disease domains. These domains are shown in Figure 2. The Cardiovascular Disease (CVD) domain accounts for over half of these cases. This is understandable since CVDs are the largest single contributor to global mortality [8]. The constituent monitoring scenarios classified under the cardiovascular domain are shown in Table 4.

Fitness monitoring refers to cases where the MVI did not target a specific domain. These cases were basically for monitoring general health and fitness. They accounted for about a quarter of the cases. The musculoskeletal domain addressed areas like fall

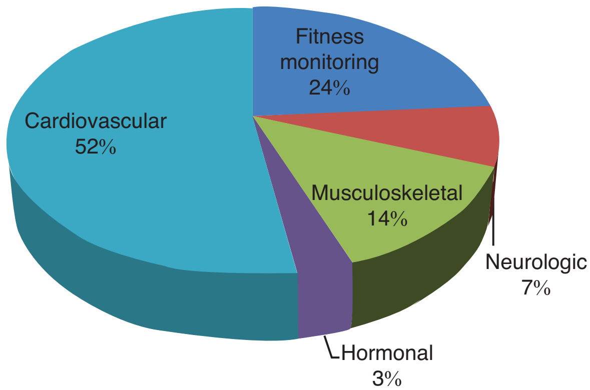

Figure 2. MVI disease domains.

Table 4. Monitoring scenarios for the cardiovascular domain

S/No.	Monitoring Scenario	No of Cases
1.	Heart monitoring [12, 19, 20, 23, 24, 31, 34, 35]	8
2.	Chronic heart failure [11,21]	2
3.	Spirometry [29]	1
4.	Hypertension [25]	2
5.	Blood flow velocity [18]	1
6.	Obstructive sleep apnea [28]	1
	Total	**15**

detection, gait analysis, and back pain. The cases classified under the neurologic domain focused on mental health monitoring using EEG sensors in the first case [24], and in the second case, an EDA sensor [27] for monitoring drowsiness. In a case involving the hormonal disease domain, blood glucose levels were monitored for the management of diabetes [23].

3.2.2. Modality

The modality refers to the expected effect on the state of health of the patient. 92.3% of the cases reviewed focused solely on extracting, analyzing, and reporting a patient's bio-signals. Only 2 MVI systems (7.7%) triggered some form of therapeutic activity in response to the results of the analysis. The first case controlled the delivery of insulin to the diabetic patient [23] and the second case involved a stimulation to help keep the sleeping patient from snoring [28].

3.2.3. System Adaptability

Implicit in the name 'personalized health monitoring' is a need to have systems that are individually suited to the needs of a patient. This requires that the systems support some level of adaptability. The high level of flexibility in MVIs makes them a ready fit for such

Table 5. Common algorithms used in MVIs

Algorithm	Cases
Pan-Tompkins [21, 24, 27]	3
Peak detection [14, 26, 34]	3
Thresholding [14,15]	2
Wavelet transform [31,35]	2
Correlation [18]	1
Fuzzy-based [20]	1
Machine learning [30]	1
Least squares [16]	1
Edge detection [26]	1

a requirement. A total of 11 (42.3%) of the reviewed articles supported some level of adaptation [12, 13, 21, 23, 27, 28, 29, 31, 33, 34, 36], most of which were adaptation at the communication and architectural levels rather than at the patient level. Five of the six cases with adaptation at the subject level [12, 28, 29, 33, 34] were based on the subject's clinical profile. The sixth case was based on the activity state of the subject [27].

3.2.4. Algorithms

Algorithms help patients and physicians make sense of the bio-signals generated by the subject. The type of disease domain and the amount of resources available on the MVI are some of the determinants of the type of algorithm used. Table 5 shows a list of the algorithms that were explicitly stated by the authors of the reviewed articles. The Pan-Tompkins algorithm was featured in the most number of cases (3) and was used for MVIs targeting the cardiovascular domain, due to their real-time suitability and resource-light processing of ECG signals. Peak detection algorithms were also used in 3 of the MVIs.

3.2.5. Outcomes/Results

Some key outcomes were reported in the studies on the use of MVIs for PHM when compared to traditional medical instruments. These outcomes were based on the three areas listed below:

1. *Effect on utility of the medical device*. Common reported outcomes included:
    a. Miniaturization of traditional medical instruments [13, 14, 16, 27, 28, 29, 32]
    b. Reduced operator bias; enabling a more quantitative based analysis [13, 15, 33, 34]
    c. Monitoring of device parameters [19]
2. *Effect on healthcare*. Common reported outcomes included:
    a. Early detection of diseases [11, 12, 21]
    b. Lower healthcare cost [23, 35, 36]
    c. Reduced need for follow up and hospitalization [11,12]

3. *Effect on the perception and satisfaction of the patient:*
    a. Patient feedback on usefulness of system [21,27]

Many of the studies reported that the MVI approach led to a positive effect on the *utility of the medical devices* [11, 12, 13, 14, 15, 16, 19, 21, 23, 27, 28, 29, 32, 33, 34, 35, 36]. Miniaturization was mentioned in these studies as the most important motivation for using MVIs. MVIs enable physicians to quantify the progression of disease and enable them to make informed choices that are not affected by the bias of operators that utilized equivalent traditional medical instruments. CIEDs and other implanted devices can be monitored with MVIs, as confirmed by one of the studies regarding the monitoring of leads, battery level, and device impedance [19].

The *effect of MVIs on healthcare* was another key category mentioned. Early detection of disease was the most important goal of the PHM systems mentioned in this category. Some studies also showed that the use of MVIs can lead to a reduction in the cost of the medical equipment and, by extension, also lead to a reduction in healthcare costs. Systems ranging anywhere between $1.000 and $50,000 could be replaced with a system costing approximately $25. A $1,000, 11 sensor system could be replaced with a much cheaper, one sensor system [36]. Two studies also mentioned a reduction in the need for hospitalization and follow up appointments as an outcome for this category.

The third category of outcomes related to the perception and satisfaction of the patient. A few studies handed out questionnaires to the users of the system to assess the level of its perceived usefulness. In all of the reported cases, the patients found the systems useful.

4. DISCUSSION

This review discusses systems that have involved the use of medical virtual instruments for PHM. PHM systems can support the paradigm shift of global healthcare and its evolving focus from curative to preventive medicine. However, in order to ensure that PHM systems can support non-fitness related health monitoring, they must enable monitoring that addresses a wider range of health challenges. To achieve this, it is important to ensure that these systems incorporate *sophisticated medical instruments*. Unfortunately, such instruments tend to be complicated, large, and expensive, creating challenges for the PHM systems to provide simplicity, portability, and cost effectiveness. MVIs provide a veritable tool for bridging the gap between the needs of PHM systems and hospital-based health-monitoring systems that utilize traditional medical instruments.

Although the articles reviewed highlight several advantages of the MVI approach, much research is still needed in order to make MVI-based PHM systems attain a level of dependability and utility comparable to those offered by traditional medical instruments in the clinical setting. For one, on the issue of *personalization*, less than a quarter of the articles supported any kind of system adaptation that was based on the profile of the patient. Furthermore, the desired level of adaptability will be attained when MVIs can reconfigure themselves according to the genomic characteristics of the subject. In the same vein, MVIs need to advance beyond the current state of being used merely for patient monitoring. They need to start supporting *therapeutic applications* for PHM systems.

System *reliability and quality of service* need to be guaranteed for patients and physicians so that each can have the same level of confidence in MVIs as they do in traditional medical instruments. Issues like ensuring accurate medical alerts and, in effect, reducing false alarms are the initial areas that need to be addressed. MVIs are not as standardized as traditional medical instruments and may still require extended, and often complicated training sessions in order to provide reliable results. This can reduce the usability and adoption level of the systems. The approach in one of the studies involved the employment of an MVI that reduced the need for *system training* to the barest minimum [34]. Such an approach can aid in the evolution and acceptance of MVIs.

The high levels of sensitivity of health records make *privacy, security, and authentication* issues of prime importance. Six of the reviewed articles (23.1% of the cases) used encryption techniques to protect patient data. Another article [33] investigated an interesting concept of e-consents to support privacy. Virtual sensing can provide an interesting approach to privacy and confidentiality. For instance, a cloud service library containing several MVIs can be developed with the ability to screen for different types of diseases. An interested subject can then use a virtual sensing approach to generate a proxy signal without having to visit the hospital to get the standard bio-signals required for the given test. The subject can then upload this signal to the disease search engine and retrieve the results that indicate the presence or absence of the diseases that were screened for. In order to increase confidentiality, the system can be developed to use the biometrics of the subject for the bio-signal upload and the result download processes.

The requirement for mobility in PHM systems comes with a need for flexible and less power- hungry applications. Generally, these systems use batteries as their power sources. However, continuous real-time monitoring easily drains batteries. Alternative *power options* can enhance the utility value of MVIs. For example, power-harvesting techniques prove to be useful. Other options include power via wireless magnetic telemetry. [25].

More research is needed to *expand the variety of MVIs* beyond the systems that mainly focus on cardiovascular health. For example, mental health is becoming a global healthcare concern. It has been reported that one in four people now experience a mental health issue in their lifetime [9]. Surprisingly, only one of the reviewed studies that used MVIs were based on bio-signals from the brain [34]. Researchers should be taking advantage of the low-cost option provided by EEG sensors to monitor brain signals. There are encouraging signs that MVIs are growing in scope and sophistication [40]. Examples include their use for biomedical imaging [41], monitoring Parkinson's disease [42,43], and respiratory disease [44,45].

Non-invasiveness and non-intrusiveness are two words that describe the desired type of sensors for MVIs. The sensors play an important role in determining the quality of the signals being monitored. However, bio-signals from a number of the non-invasive or non-intrusive sensors do not generally provide health information as detailed as those from invasive tests performed at a hospital. For example, 644 tests are performed with body fluids [10]. One would not expect MVIs to carry out as many tests, but it still shows that greatly increasing the number of possible tests would aid in the development of MVIs. *Virtual sensing* provides an opportunity to use the current non-invasive bio-signals to simulate the more invasive bio-signals. For example, one study obviates the need for expensive and complex polysomnography equipment by inferring its readings from a virtual sensor [35]. The virtual sensor was based on a pressure sensor embedded in a pillow. Also, capacitive sensing techniques mentioned in [31] can be useful in the development of more non-intrusive sensors.

A typical *healthcare workflow includes,* but is not limited to aspects like diagnosis, decision-making, treatment, and administrative procedures [46]. The use of MVIs would affect at least two of these aspects–most likely diagnosis and decision-making. As such, it may be necessary to redesign the healthcare workflow and organizational models to accommodate the use of MVIs. In a similar vein, *reimbursement* schemes need to include workflows that are based on the use of MVIs.

The results of this work are in line with some of the orientations described in European Community's report entitled "COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS–on telemedicine for the benefit of patients, healthcare systems and society" [47]. For instance, the report mentioned the importance of integrating telemedicine into the healthcare workflow. It also identifies the support of seniors, the reduction of hospital visits, and the reduction in healthcare costs as potential benefits of telemedicine and health monitoring.

One more thing to note about the challenges and future perspectives of MVI in PHM relates to the potential of *webservers* as a tool for decoupling the monitoring process from the limitations imposed by location. By taking advantage of miniaturized integrated circuits and microprocessors, MVIs can provide sensors that immediately transfer the signals to an always-on, local or remote webserver. This would enable real-time monitoring and allow all authorized persons to simultaneously view the signals. It would also allow MVIs to take advantage of the huge memory and processing capabilities of cloud computing.

There are a number of *limitations* in this review. First, the studies were based on projects managed by universities and other research institutes, not by hospitals. As such, not many of the covered systems have become mainstream commercial solutions continuously deployed in real-life environments. Second, there were few clinical trials and many were simulation studies. For those assessed with human subjects, many had small sample sizes and were based on a short test period. However, a number of trials involving CIEDs had large sample sizes. For example, 1650 patients in 75 Italian centers were monitored for periods ranging from 10-31 months [48].

Thirdly, only three of the studies gave details of the cost of implementation, making it difficult to directly compare with equivalent traditional medical instruments. Furthermore, with the rapid evolution of medical research and technology, there could be many implemented projects whose findings have not yet been published. As such, it is likely that this review has underestimated some of the current applications and techniques involving MVIs.

5. CONCLUSIONS

In this systematic review, we have identified the main modules of PHM-oriented instrumentation and the issues that determine their utility. To a large extent, current PHM systems are mainly used for fitness monitoring and niche applications. This should change, and PHM instrumentation should support a greater level of adaptability and dependability in order to become a system of choice in today's healthcare tool chain. The review shows that research on the use of MVIs in PHM is still in its infancy with many challenges to overcome. However, despite the challenges, it holds the unique promise of providing the patients with customizable medical instrumentation, at an affordable cost, in the comfort of their homes.

ACKNOWLEDGEMENT

This work was supported in part by research funds from Chosun University (2014–2015).

CONFLICT OF INTEREST

The authors indicate no potential conflicts of interest in this work.

REFERENCES

[1] Pärkkä J. *Analysis of Personal Health Monitoring Data for Physical Activity Recognition and Assessment of Energy Expenditure, Mental Load and Stress*. PhD Dissertation, Tampere University of Technology, 2011.

[2] Jayadevappa R and Chhatre S. Patient Centered Care - A Conceptual Model and Review of the State of the Art. *The Open Health Services and Policy Journal*, 2011, 4:5–25.

[3] Billis A, Papageorgiou E, Frantzidis C, Tsatali M, Tsolaki A, Bamidis P. A Decision-Support Framework for promoting Independent Living and Ageing Well. *IEEE Journal of Biomedical and Health Informatics*. 2014 Jul 25.

[4] Díaz-Rodríguez N, Cadahía OL, Cuéllar MP, Lilius J and Calvo-Flores MD. Handling real-world context awareness, uncertainty and vagueness in real-time human activity tracking and recognition with a fuzzy ontology-based hybrid method. *Sensors (Basel)*. 2014, 14(10):18131–71. doi: 10.3390/s141018131.

[5] Qiua X-J, Zhengb W-H, Tanga Y-T and Lua F. The Test Verification Design Method Based on Rapid Prototyping Technology of Aero-engine. *Procedia Engineering*. 2015, 99:981–990.

[6] Adeluyi O and Lee J-A. Medical Virtual Instrumentation for Ambient Assisted Living: Part 1 Concepts. *Measurement and Control Journal*. 2015, 48(6):167–177.

[7] Olansen JB and Rosow E. *Virtual Bio-Instrumentation: Biomedical, Clinical, and Healthcare Applications in LabVIEW*. Prentice Hall PTR, New Jersey 2001.

[8] Promoting Cardiovascular Health in the Developing World: A Critical Challenge to Achieve Global Health. Institute of Medicine (US) Committee on Preventing the Global Epidemic of Cardiovascular Disease: Meeting the Challenges in Developing Countries, Fuster V, Kelly BB (Eds). Washington (DC): National Academies Press (US), 2010.

[9] Votruba N and Thornicroft G. The importance of mental health in the Sustainable Development Goals. *BJPsych International* 2015,12(1):2–4.

[10] A-Z list of laboratory tests at the Central Manchester University Hospitals, United Kingdom, *www.cmft.nhs.uk/info-for-health-professionals/laboratory-medicine/a-z-list-of-laboratory-tests*. Accessed June 3, 2015.

[11] Koehler F, Winkler S, Schieber M, Sechtem U, Stangl K, Böhm M, Boll H, Baumann G, Honold M, Koehler K, Gelbrich G, Kirwan BA and Anker SD. Impact of remote telemedical management on mortality and hospitalizations in ambulatory patients with chronic heart failure: the telemedical interventional monitoring in heart failure study. *Circulation*. 2011, 123(17):1873–80. doi: 10.1161/CIRCULATIONAHA.111.018473.

[12] Ricci RP, Morichelli L and Santini M. Remote control of implanted devices through Home Monitoring technology improves detection and clinical management of atrial fibrillation. *Europace 2009*, 11(1):54–61. doi:10.1093/europace/eun303.

[13] Guerri JC, Antón AB, Pajares A, Monfort M and Sánchez D. A mobile device application applied to low back disorders. *Multimedia Tools and Applications*. 2009, 42(3):317–340.

[14] Kang JM, Yoo T and Kim H-C. A Wrist-Worn Integrated Health Monitoring Instrument with a Tele-Reporting Device for Telemedicine and Telecare. *IEEE Transactions on Instrumentation and Measurement*.2006,55(5):1655–1662.

[15] Tsanas A, Little MA, McSharry PE and Ramig LO. Accurate telemonitoring of Parkinson's disease progression by noninvasive speech tests. IEEE Transactions on Biomedical Engineering. 2010, 57(4):884–93. doi:10.1109/TBME.2009.2036000.

[16] Dellacà RL, Gobbi A, Pastena M, Pedotti A and Celli B. Home monitoring of within-breath respiratory mechanics by a simple and automatic forced oscillation technique device. *Physiological Measurements*. 2010, 31(4):N11-24. doi:10.1088/0967–3334/31/4/N01.

[17] Harini M, Bhairavi K, Gopicharan R, Ganapathy K and Vaidehi V. Virtualization of healthcare sensors in cloud. *2013 International Conference on Recent Trends in Information Technology (ICRTIT)*. 2013: 663–667.

[18] Madria S, Kumar V and Dalvi R. Sensor Cloud: A Cloud of Virtual Sensors. *IEEE Software*. 2014, 31(2):70–77, DOI Bookmark: http://doi.ieeecomputersociety.org/10.1109/MS.2013.141.

[19] Sticherling C, Kühne M, Schaer B, Altmann D and Osswald S. Remote monitoring of cardiovascular implantable electronic devices: prerequisite or luxury? Swiss Medical Weekly. 2009, 139(41–42):596–601. doi:smw–12667

[20] Wang H, Peng D, Wang W, Sharif H, Chen H-H and Khoynezhad AA. Resource-aware secure ECG healthcare monitoring through body sensor networks. *IEEE Wireless Communications*. 2010, 17(1): 12–19.

[21] Fanucci L, Saponara S, Bacchillone T, Donati M, Barba P, Sánchez-Tato I and Carmona C. Sensing Devices and Sensor Signal Processing for Remote Monitoring of Vital Signs in CHF Patients. *IEEE Transactions on Instrumentation and Measurement*. 2013, 62(3):553–569.

[22] Lee S-J, Kim J and Lee M. The Design of the m-Health Service Application Using a Nintendo DS Game Console. Telemedicine and e-Health 2011, 17(2):124–30. doi:10.1089/tmj.2010.0080. Epub 2011 Jan 9.

[23] Dilmaghani RS, Bobarshad H, Ghavami M, Choobkar S and Wolfe C. Wireless sensor networks for monitoring physiological signals of multiple patients. *IEEE Transactions on Biomedical Circuits and Systems*. 2011, 5(4):347–56. doi:10.1109/TBCAS.2011.2114661.

[24] Hii P-C and Chung W-Y. A Comprehensive Ubiquitous Healthcare Solution on an Android™ Mobile Device. *Sensors (Basel)*. 2011,11(7):6799–6815. Published online Jun 29, 2011. doi: 10.3390/s110706799, PMCID: PMC3231662.

[25] Cleven NJ, Müntjes JA, Fassbender H, Urban U, Görtz M, Vogt H, Gräfe M, Göttsche T, Penzkofer T, Schmitz-Rode T and Mokwa W. A novel fully implantable wireless sensor system for monitoring hypertension patients. *IEEE Transactions on Biomedical Engineering*. 2012, 59(11):3124–30. doi: 10.1109/TBME.2012.2216262.

[26] Pitts DG, Patel MK, Lang PO, Sinclair AJ and Aspinall R. A respiratory monitoring device based on clavicular motion. *Physiological Measurements*. 2013, 34(8):N51–61. doi: 10.1088/0967–3334/34/8/N51.

[27] Anliker U, Ward JA, Lukowicz P, Tröster G, Dolveck F, Baer M, Keita F, Schenker EB, Catarsi F, Coluccini L, Belardinelli A, Shklarski D, Alon M, Hirt E, Schmid R and Vuskovic M. AMON: a wearable multiparameter medical monitoring and alert system. *IEEE Transactions on Information Technology in Biomedicine*. 2004, 8(4):415–27.

[28] Cheng CM, Hsu YL, Young CM and Wu CH. Development of a portable device for telemonitoring of snoring and obstructive sleep apnea syndrome symptoms. *Telemedicine and e-Health*. 2008, 14(1):55–68. doi: 10.1089/tmj.2007.0022.

[29] Chun H, Kang J, Kim KJ, Park KS and Kim HC. IT-based diagnostic instrumentation systems for personalized healthcare services. *Studies in Health Technology and Informatics*. 2005, 117:180–90.

[30] Yu Y, Li J and Liu J. M-HELP: a miniaturized total health examination system launched on a mobile phone platform. *Telemedicine and e-Health*. 2013, 19(11):857–65. doi:10.1089/tmj.2013.0031.

[31] Fong E-M and Chung W-Y. Mobile Cloud-Computing-Based Healthcare Service by Noncontact ECG Monitoring. *Sensors (Basel)*. 2013, 13(12):16451–16473. doi:10.3390/s131216451.

[32] Giansanti D, Morelli S, Maccioni G and Grigioni M. Portable kit for the assessment of gait parameters in daily telerehabilitation. Telemedicine and e-Health. 2013,19(3):224–32. doi: 10.1089/tmj.2012.0091.

[33] Gómez EJ, Hernando Pérez ME, Vering T, Rigla Cros M, Bott O, García-Sáez G, Pretschner P, Brugués E, Schnell O, Patte C, Bergmann J, Dudde R and de Leiva. A. The INCA system: a further step towards a telemedical artificial pancreas. *IEEE Transactions on Information Technology in Biomedicine*. 2008, 12(4):470–9. doi:10.1109/TITB.2007.902162.

[34] D'Arcy RC, Hajra SG, Liu C, Sculthorpe LD and Weaver DF. Towards brain first-aid: a diagnostic device for conscious awareness. *IEEE Transactions on Biomedical Engineering*. 2011, 58(3):750–4. doi: 10.1109/TBME.2010.2090880. Epub 2010 Nov 11.

[35] Chen W, Zhu X, Nemoto T, Kitamura K, Sugitani K and Wei D. Unconstrained monitoring of long-term heart and breath rates during sleep. *Physiological Measurements*. 2008, 29(2):N1–10. doi: 10.1088/0967–3334/29/2/N01.

[36] Nemiroski A, Christodouleas DC, Hennek JW, Kumar AA, Maxwell EJ, Fernández-Abedul MT and Whitesides GM. Universal mobile electrochemical detector designed for use in resource-limited applications. *Proceedings of the National Academy of Sciences of the United States of America*. 2014, 111(33):11984–11989, Bell AT (ed). doi: 10.1073/pnas.1405679111.

[37] Lee Y, Lee B and Lee M. Wearable sensor glove based on conducting fabric using electrodermal activity and pulse-wave sensors for e-health application. Telemedicine and e-Health, 2010, 16(2):209–17. doi:10.1089/tmj.2009.0039.

[38] The BioMobius Platform. http://www.capsil.org/capsilwiki/index.php/BioMOBIUS. Accessed June 2 2015.

[39] The Reconfigurable Virtual Instrument FPGA Platform. http://mlab.ictp.it/rvi/system.html. Accessed June 2 2015.

[40] Special Issue on Mobile Medicine. Annals of Biomedical Engineering. 2014, 42(11):2203–2204.

[41] Roy M, Seo D, Oh CH, Nam MH, Kim YJ and Seo S. Low-cost telemedicine device performing cell and particle size measurement based on lens-free shadow imaging technology. Biosensors and Bioelectronics. 2015, 15,67:715–23. doi:10.1016/j.bios.2014.10.040.

[42] Barroso MC, Esteves GP, Nunes TP, Silva LMG, Faria ACD and Melo PL. A telemedicine instrument for remote evaluation of tremor: design and initial applications in fatigue and patients with Parkinson's Disease *BioMedical Engineering OnLine*. 2011, 10:14. doi:10.1186/1475–925X–10–14.

[43] Patel S, Chen BR, Buckley T, Rednic R, McClure D, Tarsy D, Shih L, Dy J, Welsh M, Bonato P. Home monitoring of patients with Parkinson's disease via wearable technology and a web-based application. 2010 Conf Proc IEEE Eng Med Biol Soc. 2010, 4411–4. doi:10.1109/IEMBS.2010.5627124.

[44] da Silva Junior EP, Esteves GP, Dames KK, Melo PL. A telemedicine instrument for Internet-based home monitoring of thoracoabdominal motion in patients with respiratory diseases. Review of Scientific Instruments. 2011, 82(1):014301. doi:10.1063/1.3529443.

[45] Silva Junior EP1, Esteves GP, Faria AC, Melo PL. An internet-based system for home monitoring of respiratory muscle disorders. IEEE Eng Med Biol Soc Conf Proc. 2010,2010:5492–5. doi: 10.1109/IEMBS.2010.5626581.

[46] Macedo M and Isais P. Standards Related to Interoperability in EHR & HS, in: Sicilia M.A. and Balazote P (eds). *Interoperability in Healthcare Information Systems: Standards, Management, and Technology: Standards, Management, and Technology*. 2013:19–44.

[47] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - on telemedicine for the benefit of patients, healthcare systems and society. *http://www.ipex.eu/IPEXL-WEB/dossier/dossier.do?code=COM&year=2008&number=0689*. Accessed June 1 2015.

[48] Ricci RP, Morichelli L, D'Onofrio A, Calò L, Vaccari D, Zanotto G, Curnis A, Buja G, Rovai N, Gargaro A. Manpower and Outpatient Clinic Workload for Remote Monitoring of Patients with Cardiac Implantable Electronic Devices: Data from the HomeGuide Registry. *Journal of Cardiovascular Electrophysiology*. 2014, 25(11):1216–23.

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
1.	Koehler et al. [11]	2011	Circulation (Journal of the American Heart Association).	12-lead ECG, BP, Weight; Dynamic encryption on cell phone; PDA (Central Device), Bluetooth (Communication).	Impact of remote monitoring on Chronic Heart Failure.		710 stable chronic heart failure patients; 17-month (duration); Low statistical power (limitation); Study evaluated effect of remote telemonitoring on mortality.	Primary outcome: Rate of cause mortality (death) was reduced to 8.4% as compared with 8.7% for normal care. Secondary outcome: Cardiovascular death and hospitalization per 100 person years of follow up reduced to 14.7% as compared to 16.5% for normal care.
2.	Ricci et al. [12]	2009	Eurospace (Europe Society for Cardiology).	Home monitoring, long distance telemetry, automatic transmission of pacemaker data on a daily basis. Implanted cardio device (ICD) with wireless telemetry via a GSM phone as encrypted sms.	Impact of home monitoring on Atrial Fibrillation (AF).	Pacemaker and ICD programming was tailored to patient's individual clinical profile.	166 patients for 2 years.	Remote monitoring led to AF detection and alert that occurred an average of 148 days before scheduled follow up visit. Limitation: It was an observational study with no clinical outcome.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
				Data transmitted every night and critical conditions are reported to service center within 3 minutes. Error detection to distinguish between true arrhythmias and R-wave far field oversensing.				Open issue: how to select appropriate alerts.
3.	Guerri et al. [13]	2009	Multimedia Tools and Applications.	8-channel Surface EMG, portable handheld prototype (Platform), connected to phone/ PDA via WiFi; PDA: HP IPAQ HX4700, phone: Nokia E41; includes online telemetry mode and offline mode (with storage on CF card).	Use of mobile devices and wireless networking for assessment of muscular conditions.	Configured via a mobile device. Configuration was based on patient's profile or system parameters like duration of exercise, sampling frequency and monitored muscle. Config modes: offline and online.	Duration: 55 seconds. Phase 1: feasibility and reliability: 12 volunteers. Phase 2: usability assessment: questionnaires completed by 7 users.	Design of a portable device capable of advanced EMG measurements. Can be used by both expert and non-expert users.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
4.	Kang et al. [14]	2006	IEEE Transactions on Instrumentation and Measurement.	Wrist worn device with 6 biosensors for: (i) Fall detection [2-axis accelerometer, gyroscope and in-house posture sensor], (ii) 1-channel ECG textile electrode, (iii) Noninvasive BP [based on a wrist cuff], (iv) SPO2, (v) Respiratory Rate [based on Virtual sensing of r-r intervals of ECG], and (vi) Body Surface Temperature. A cellular phone was used as the connection gateway; wireless connection used between wrist worn device and phone; CDMA was used for connection between the phone and medical service center. Main algorithms were based on thresholding.	Wrist-worn device for general health monitoring. Anomalies were reported via sms.		Limitation: Low fidelity of biosignals since most measurements were based on readings from the the skin. Tests were based on simulated signals and human trials.	Error Range and Detection Rates: ±5mmHg for NIBP, 2% for SPO2, 1% for ECG, 1.8% for respiration rate, 1.5% for temperature, 91.3% detection rate for 150 simulated falls.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
5.	Tsanas et al. [15]	2010	IEEE Transactions on Biomedical Engineering.	Virtual sensing based on speech tests from a microphone headset on an Intel AHTD Telemonitoring System for predicting Parkinson's Disease (PD). Algorithm was based on thresholding. Speech signal processing was based on 16 dysphoni a measures applied to 5923 sustained phonations.	Accurate system for tracking the progression of Parkinson's Disease Rating Scale (UPDRS). Statististical mapping of a subset of speech features to UPDRS. It showed the potential of vowel phonations in predicting average PD progression.		It was based on 6,000 database recordings from 42 PD patients. Based on objective (rather than subjective) assessment. Human trial was based on a 6 month study of 42 idiopathic PD patients.	This virtual sensing approach can estimate the result within about 7.5. UPDRS points difference from the clinicians' estimates using a simple, self-administered non-invasive test.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
6.	Dellaca et al. [16]	2010	Physiological Measurement.	Pressure and flow sensors. Respiratory input impedance (Zrs) was measured after a 5Hz pressure stimulus from a loudspeaker was transmitted to the patient through a self-made mesh-type Pneumotachograph (PNT). Zrs was computed using the Least squares algorithm and transmitted over the Internet. Communication was based on GPRS, DSL or WiFi (depending on availability).	Forced Oscillation Technique (FOT) device for unsupervised monitoring to replace supervised spirometry. Useful for diagnosis and staging of obstructive diseases (like COPD and asthma).		5 healthy subjects, 36 consecutive daily home measurements. Reduces the dimensions of current FOT device. 36 consecutive daily home measurements. Extensive tests on 7 subjects. Limitation: Only 1 COPD patient was used in the tests.	The portable FOT device can be used for unsupervised assessment of airway obstruction over prolonged periods. The maximum error was 10%.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
				Encryption was based on Public Key Algorithm. Realtime or scheduled transmission options were available. Reliable and standardized TCP/IP connection was established by using SSH.				
7.	Sticherling et al. [19]	2009	Swiss Medical Weekly.	CIED; based on an optivol sensor that measured intrathoracic impedance upon the accumulation of intrapulmonary fluid. GSM was used for remote monitoring.	Remote monitoring of ICDs for early detection of disease and device anomaly. It was also used to number of patient visits to the hospital.		It was a survey.	

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
8.	Wang et al. [20]	2010	IEEE Wireless Communications.	It used a 3-lead ECG sensor with a transmission range of 100 m. It used a low delay adaptive encryption scheme dependent on the condition of the wireless channel.	Secure and resource aware body sensor network architecture for real-time health monitoring based on unequal resource allocations. It used an on-body healthnode data terminal to process and transmit sensor data.		The system allocated extra energy resources to protect the important portion of the transmitted signal.	The tests were based on simulation and real time tests. This lowered energy consumption and gave better signal quality per energy used. Authors stated that shorter QRS windows can improve real-time encryption.
9.	Fanucci et al. [21]	2013	IEEE Transactions on Instrumentation and Measurement.	7 Sensors: (i) 3-lead ECG (ii) SPO2 (iii) BP (iv) Weight (v) Chest impedance (vi) Respiration (vii) Posture. Local-MVI communication: Bluetooth Remote-MVI communication: ADSL or	Flexible and highly configurable system for monitoring Chronic Health Failure (CHF). It provided alerts for abnormal	Configuration parameters: Alarm thresholds, transmission policy, selectable symptoms. It also supported remote configuration.	One or few non-continuous daily measurements were made.	ECG simulators and Physionet Toolkit were used for analysis. Pre-prototype tests: 2 patients, 1 month test. Post-prototype tests: 30 patients with Chronic Heath Failure disease.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
				mobile broadband. HTTPS used for security and encryption. A prototype was built and the Pan-Tompkins algorithm was used for ECG analysis.	heart frequency, atrial fibrillation episodes, QRS complexes exceeding 120 ms and signs of myocardial ischemia.			Results: <3% activity misses (mostly in the 1st days). <5% false positive alarms, 95% patients found the system useful and 99% patients were satisfied with system.
10.	Lee et al. [22]	2011	Telemedicine and e-Health.	The system used a Nintendo DS Game Console as the platform. However, the system can also use a PC or PDA. 3-channel ECG, 3-axis accelerometer (±3 g), Tilting (Sensors). 1 ECG packet consists of 64 ECG signals. ZigBee was used for the local-MVI communication while WiFi was used for the Remote-MVI	Mobile health ECG and gait monitoring system that obviates distance restrictions.			It used a 1-hour test to ensure appropriate wireless connectivity. The health monitoring test lasted for over 24 hours without any interruption. Packet loss: <5% for distances less than 20 m, much higher and incremental loss beyond 20 m For packet error rate (Pe):

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
				communication. The system also included a webserver.				When Pe = 0, no delay; Pe = 0.2, 25s delay and Pe = 0.4, 157s delay (due to the need for retransmission).
11.	Dilmaghani et al. [23]	2011	IEEE Transactions on Biomedical Circuits and Systems.	ECG (Sensor). Its Wireless Patient Portable Unit (Platform) had a webserver and connected to a central remote node via Internet access provided by a Wireless Access Point Unit (WAPU).	System to monitor patients with chronic diseases in their homes.	WPPU can be configured for a variable gain between 500 and 1000.	The study avoided the use of a PC and PDA (to reduce cost). System objectives: Eliminate the need for a PC, eliminate the need for users to configure the system, support automatic transmission of signals, lower cost, and increase ease of use.	Same quality of service as PC based systems at a lower cost.
12.	Hii and Chung [24]	2011	Sensors (Basel).	ECG, Smartphone camera (Sensors). The system was based on 3 layers, namely: (i) Body	Mobile phone based real time ECG monitoring. It took advantage			Successful ealtime monitoring on a testbed with a human subject.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
				Sensor Layer [ECG nodes on body] (ii) Personal Network Layer [Mobile phone] (iii) Global Network Layer. Platform: mobile phone. Local-MVI communication: ZigBee. Remote-MVI communication: CDMA, GSM, 3G or WiFi. Modes: real-time (immediately viewable on phone) or Store-and-forward (20 byte ECG data and summary reports transferred to the remote end). One ECG data packet contained 10 ECG signals (phone screen could display 5 packets, equivalent to 5 s of data). Algorithm: Pan-Tompkins (The analysis was for	of the falling cost and rising complexity of mobile phones. A QR code scanner was used to determine patient adherence.			

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
				QRS peaks, QT and RR intervals). The camera was used for scanning the QR barcodes on medicine packs.				
13.	Cleven et al. [25]	2012	IEEE Transactions on Biomedical Engineering.	Capacitive pressure and temperature (Sensors). Measured intraarterterial pressure using an implant consisting of a sensor tip and transponder communicating with a readout station. Local-MVI communication: Inductive coupling. The pressure sensor was powered using wireless magnetic telemetry.	Wireless BP measurement.		A batteryless system that uses an implant into the Femoral artery. The implant consists of a pressure sensor and telemetric unit and was placed under the skin.	The trial used an anesthesized sheep and readings were compared to a reference catheter. The system had an accuracy of ±1.0 mmHg and a range of 30-300 mmHg.
14.	Pitts et al [26]	2013	Physiological Measurements.	Accelerometer (Sensor). The algorithm was based on peak and edge detection.	Simple low cost device for measuring respiratory rate		Respiratory sensor based on clavicular motion. A clavicular	R2 values mean clavicular respiratory rate: 0.89 (lateral) and 0.98 (longitudinal),

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
				The system provided virtual sensing of respiratory rate based on the longitudinal (Z) axis reading of the accelerometer placed on the patient's clavicle.	and inferring disease if the rate falls outside the 12-20 breadth/ minute rate of healthy adults.		sensor was used since it gave signals with a greater amplitude and which were more consistent than thoracic sensors. The system was tested on 8 volunteers.	compared to 0.49 (thoracic). System was unaffected by bioelectrical or electrode problems. A 4-min breath-by-breadth test period was used.
15.	Anliker et al. [27]	2004	IEEE Transactions on Information Technology in Biomedicine.	Blood pressure, SPO2, 1/12-lead ECG, 2-axis accelerometer, pulse, heart rate, temperature (Sensors). Data was encrypted using techniques inherent in GSM/GPRS. Algorithm: Pan-Tompkins.	Unobstrusive wrist-worn multiparametric monitoring system.	Configuration was based on patient specific values: non aerobic/aerobic state (corresponding to level of user activity), age, gender, fitness and medical history.	The study incorporated the patient's profile in order to reduce false alarms. It measured pulse and SPO2 continuously. BP and 30 s of ECG were measured 3 times a day or at request of user. The user's	33 volunteers participated in a 70-min test. Results: For BP, 85% had a difference of less than 5 beats when compared to standard instruments. The ECG results were poor as a result of noise but other readings were ok.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
							health condition/ equipment state was grouped into the following zones based on the results: (i) normal, (ii) deviant, (iii) risk, (iv) high risk, and (v) system error	70% of users found he system comfortable.
16.	Chung et al. [28]	2008	Telemedicine and e-Health.	Microphone-an omnidirectional electrets condenser-type (Sensor). System used the measured signals for the virtual sensing of Obstructive Sleep Apnea Syndrome (OSAS). System supported both monitoring and therapeutic applications. The therapeutic application involved nerve stimulation using a low frequency	A portable telemonitoring device to recognize sleep-related breathing disorders in real-time	Configuration was based on the detection of a snoring pattern. The detection triggered a system configuration that stimulated the patient's nerve in order to stop the snoring.	5 regular snorers and 5 OSAS patients tested the system.	There was a positive predictivity of 94% and a snoring sensitivity of 94%. The results indicated an OSAS positive predictivity and sensitivity of 73.3% and 81.1% respectively.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
				transcutaneous electrical signal. The system included a local webserver. Algorithm: Absolute difference between input voltage and baseline and moving average filter with a window size of 20.				
17.	Chun et al. [29]	2005	Studies in Health Technology and Informatics.	Non-Invasive Blood Pressure [NIBP], SPO2, 1-channel ECG textrode electrode, Respiratory Rate [RR], Heart Rate [HR], Body surface temperature, Accelerometer, Posture (Sensors). RR and HR were virtual sensors based on ECG signals. Local-MVI	Personal Wearable Wristworn Integrated Health Monitoring Device (WIHMD).	System was configured based on patient's diabetic history and postprandial time. The BP tests also considered the patient's history.	The primary system was based on the WIHMD. The secondary system had a number of non intrusive sensors used on the bed, toilet seat and chair. Capacitive sensors were used for the chair. 10 volunteers	Simulation / Tests / Results NIBP / 100 / ±4mmg SPO2 / 100 / ±2% HR / 100 / ±0.9% RR / 50 people / ±1.8% Temp* / 20 / ±1.5 Fall# / 150 / 91.3%# *Tested in temperature controlled chamber #Detection rate for simulated falls

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
				communication: Wireless Remote-MVI communication: sms, cellular. The expanded system (Integrated Home Telecare System) comprised the following sensors: 12-channel ECG, Respiratory function, Blood glucose, NIBP, Body fat meter and Spirometer.			tested the system and authors also used simulations.	
18.	Yu et al. [30]	2013	Telemedicine and e-Health.	Temperature, mobile phone camera and microphone (Sensors). System used a mobile phone as a miniaturized health exam toolkit. Electronic health records were sent to remote server as e-mails or mms messages. Local-MVI communication: Wireless.	Mobile phone based system for convenient "annual physical exam".		Eye tests were based on image sizes on phone and feedback from users. The system was trained as follows: 3 deep breaths (for breadth sound), 1 minute data (for heart sound, temperature	The entire test took just about 28 minutes.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
				Remote-MVI communication: Cellular. Algorithms: Machine learning. System carried out tests for about 12 parameters used in annual physical exams.			and ECG). There were 11 volunteers for the test.	
19.	Fong and Chung [31]	2013	Sensors (Basel)	Platform: Android based phone. ECG, Heart Rate, Camera (Sensors). Data was shared over the Internet instantaneously using the embedded webserver. Local-MVI communication: Bluetooth communication between capacitive coupled ECG sensor and phone. Inter-MVI communication: WiFi. HR was calculated using a virtual sensor based on ECG.	Cloud-based non-contact ECG monitoring and a QR code based patient adherence scheme.	The system supported a minimal level of adaptation based on QR code.	The measurements required the patient to seat on a chair with capacitive sensors.	The results measured the website loading times as follows: 1st view load time (2.833 ms), repeat view time (0.124 ms), the Document Complete parameter, which occurs after all the images content have been loaded (2.833 s), the fully loaded parameter, which includes any activity triggered by the JavaScript (6.452 s).

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
20.	Giansanti et al. [32]	2013	Telemedicine and e-Health.	Sensors: Gastrocnemius Expansion Measurement Unit (GEMU), gyroscope, accelerometer, SECOSP (a step counter). Platform: Custom portable device.	Real-time simple portable kit for home-based gait analysis.		The portable kit works with a cascade of Instrumented Walkways (IWs). It also uses walking aids. 16 subjects tested the system.	System has a high level of accuracy and costs 948 EUR.
21.	Gomez et al. [33]	2008	IEEE Transactions on Information Technology in Biomedicine.	Realtime Continuous Glucose Monitoring (CGM) sensor. Platform: PDA (iPAQ hp2210). Local MVI: Bluetooth, Infrared or serial communication. Remote MVI: Mobile GPRS for communication to the Telemedicine Central Server (TMCS).		The PDA was remotely programmed by the TCMS under the doctor's supervision. The insulin pump was configured and controlled remotely in response to the measured CGM values.	CGM with real-time programmable insulin pumps. 4 system control strategies: (i) patient control: manual change supervised by doctor (ii) doctor control: come as suggestions that the patient should	Only control strategies #1 and #2 were tested and the measured HbA1c values confirmed the effectiveness of the strategy. System cost: 7,348 EUR (compared to 5,907 EUR for a CGM system based on a manual approach).

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
				The system supports a herapeutic application- the control of an insulin pump.			download and approve (iii) remote loop control: programmed by the TCMS under the doctor's supervision. (iv) personal loop control: real-time control of the insulin pump based on glucose sensor data The patient has to issue e-consents (digitally signed certificates) before personal data can be accessed. Feasibility testing phase: 4 Type 1 diabetic patients for 6 months. Clinical testing phase: 10 Type 1 patients for 8 weeks.	

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
22.	D'Arcy et al. [34]	2011	IEEE Transactions on Biomedical Engineering.	EEG sensor. A headset for auditory stimulation. Local-MVI Communication: Bluetooth. The algorithm was known as called Halifax Consciousness Scan (HCS). It was based on preprocessing, peak detection and score generation.	An approach for replacing the behavioral brain tests with one based on EEG signals. The test provides indicators for 5 identifiable levels of neural processing: sensation, perception, attention, memory and language.	The specific parameters of the patient are compared to a normative database.	The portable EEG device for scanning for consciousness awareness addressed 5 challenges/areas: (i) portability and noise resistance (ii) it has no need for advanced expertise or system training (iii) addressed the spectrum of EEG-cortical responses (iv) compared results to a normative database (v) the range of results covered diagnosis, reliability, validity and progression.	The authors attempted to provide a solution at the interface between biomedical engineering and neuroscience.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ- ATION	STUDY DESIGN	OUTCOME/ RESULTS
23.	Chen et al. [35]	2008	Physiological Measurements.	A pressure sensor was embedded in a pillow for static and dynamic pressure measurements. Wavelet based algorithms were used. Virtual sensing of the pressure was used to reconstruct pulse related waveform information from D4 & D5 components of wavelet transformation. Also, breadth related waveform was reconstructed from the A6 component.	Web-based long term heart and breadth rate monitoring during sleep using a single sensor.		The raw pressure was measured under the near-neck occiput region. The system measures static pressure (based on weight of head) and dynamic pressure (based on fluctuations cased by breathing). Analysis was based on the dynamic pressure. 1 patient was used to test the system over a period of 6 months.	The system detected 82.3% of sleep time. The system provided a cheap 1 sensor alternative to replace the traditional $1,000 11-sensor polysomnography equipment.

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
24.	Nemiroskia et al. [36]	2014	Proceedings of the National Academy of Sciences, USA.	A portable system that includes a vibration meter and an audio jack. This system interfaces with a low end mobile phone (Nokia 1100 series model 1112) and can also support 2G, 3G and 4G systems. The system uses a webserver to "geographically decouple" the measurement. Local-MVI communication: Standard audio cable. Remote-MVI communication: Cellular (based on a live voice link through VoIP Skype between the phone and remote system). The remote server decodes	It is an inexpensive device that couples most forms of electrochemical analysis directly to the cloud. It uses a handheld device that works in a resource-constrained environment.	The system can switch between the following modes: (i) 2 or 3 electrode system. (ii) Amperometric (iii) Potentiometric The system can also be configured to accommodate new assays, sequences and standards.	The system supports cyclic voltammetry, differential phase voltammetry, square wave voltammetry and potentiometry It supports low-end phones and does not require apps that are usually required for Smartphone based systems. The proof of concept was demonstrated in 4 application domains: (i) blood glucose (ii) trace heavy metals	The system cost just $25. It is a simple system, much unlike complex microfluidic based system. Latency (transmit and receive) for the blood glucose application was just 2.2 s. The system results for the 4 application domains were compared to results from a commercial bench-top analyzer and the following results were obtained: (i) no difference with respect to performance of the electronics. (ii) blood glucose standard deviation:

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZ-ATION	STUDY DESIGN	OUTCOME/ RESULTS
				the Frequency Shift Keying (FSK) data and sends an acknowledgement to the phone as an sms to verify the measured value.			(iii) Sodium in urine and (iv) test for malaria antigens.	5% (which is much better than most commercial glucometers). (iii) heavy metals in water: detection limit of 4 μg/L, better than the recommended WHO level of 10 μg/L. (iii) Sodium in urine: systematic error of 8%, which is within the certified range of ±14%. (iv) Malaria: limit of detection was 20 ng/mL.
25.	Lee et al. [37]	2010	Telemedicine and e-Health.	Sensors: Electrodermal Activity [EDA], Pulsewave [Condenser microphone]. The EDA sensor was	A system to detect drowsiness based on a correlation between EDA		The system investigated the correlation between skin impedance and	The detected states: - aroused condition - drowsiness - sleeping The device was able

Continued

APPENDIX A. SUMMARY OF STUDIES INCLUDED IN THE REVIEW

S/N	AUTHORS	YEAR	JOURNAL	ARCHITECTURE	APPLICATION	ADAPTATION/ PERSONALIZATION	STUDY DESIGN	OUTCOME/ RESULTS
				made of conducting fabric lines (instead of AgCl). Platform: Portable arm-band computer. Realtime processing supported by a webserver. Local-MVI communication: Serial (RS-232). The algorithm was based on Fast Fourier Transform (FFT).	signals and drowsiness.		drowsiness. The EDA signal was decomposed into 2 signals: (i) Skin Impedance Level (SIL) and (ii) Skin Impedance Response (SIR) The experiment lasted for 30 mins.	to detect drowsiness before its onset.