Towards a Mobile System for Hypertensive Outpatients' Treatment Adherence Improvement

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Abstract—**Covering more than a third of the population, arterial hypertension is a debilitating disease resulting in the adverse effect on the physical and emotional state of the patient and, hence, exerting the negative influence on the patient health-related quality of life. Treatment of hypertension involves the use of specific drug therapy along with a modification of a lifestyle and a diet over a long-term period. This, in turn, leads to the low adherence to the treatment among the ambulatory patients and, as a consequence, increases the chances of the hypertension-related complications, including the risk of sudden cardiac death. To address the problem of low adherence, we have previously proposed the mobile personal monitoring and assisting system constructed on the principles of smart spaces. The system relies on joint processing of both objective and subjective health measures accumulated in semantic ontology-driven storage enabling the construction of the personalized assisting services. In this paper, we extend the approach putting into consideration behaviour activities and interventions. Moreover, we propose the adherence assessment method based on the variety of user engagement measures, which also can be divided into subjective questionnaire-based measures, and objective metrics based on behaviour analysis and mobile app analytics.**

I. Introduction

Rapid ageing of the world's population caused the epidemiological shift from communicable to non-communicable diseases (NCDs) [1]. One of the major risk factors of NCDs and, in particular, cardiovascular diseases (CVDs) is hypertension which was defined as systolic blood pressure (SBP) of at least 140 mmHg and diastolic blood pressure (DBP) of at least 90 mmHg, self-reported use of antihypertensives, or both. According to the World Health Organization (WHO) report, arterial hypertension is the most essential preventable risk factor of premature death [2]. Having increased arterial pressure puts the individual at risk for a variety of cardiovascular diseases, which are leading causes of death all over the world, namely, stroke, coronary artery disease, heart failure, atrial fibrillation, and peripheral vascular disease. The prevalence of hypertension is estimated to be 30–40% of the world's population. In addition, about a third of the world adults has prehypertension, which was defined as SBP of 120–139 mmHg or DBP of 80–89 mmHg, i.e. blood pressure numbers that are higher than normal—but not yet in the high blood pressure range. Prehypertension is associated with increased cardiovascular risk and target organ damage compared with individuals who are normotensive.

Prevention and treatment of arterial hypertension heavily rely on behaviour change, moreover, for the majority of patients, a substantial modification of their lifestyle has prime significance [3]. Therefore, the therapy is time-consuming and it demands a self-discipline from the patient. It is shown that in a six months period more than a third, and in a year more than a half of the outpatients, give up the appointed treatment, and about 10% of the patients forget to accept medicines daily [4], [5]. Despite the high awareness of their hypertension among adults, only about half of people with high blood pressure have their condition under control. Thus, there is a problem of low adherence of the hypertensive patients to prevention and treatment, i.e., of the readiness for strict observance of the instructions appointed by the doctor both at medicines intake and at the behaviour change (e.g., of the recommendations to intensify the physical activity, stick to a healthy eating plan, etc.). The adherence to the treatment among prehypertensives is reported to be even worse.

In the previous work, we have proposed an integrated approach to hypertension management heavily relied on the use of the background intellectual environment to supervise the patient by means of the systems of personal recommendations, or intellectual assistants [6]. The proposed solution is significantly banks on the use of the information technologies, and, in particular, on the recent advances in mobile healthcare, smart environments and cloud computing. It can potentially lead to minimization of risk of complications due to improvement of prevention, early diagnostics, forecasting of development of the disease. The solution supports outpatients mobility, implements of complex collecting and the analysis of personal data and a context information, and also provides "smart" decisions and personalized recommendations according to the principles to mobile personalized medicine [7].

The proposed hypertension management assistance system is designed with the aim at the increasing of the adherence to the treatment among hypertensive patients. The health-related data are gathered from multiple sources and are stored in semantic-driven storage for the further construction of personalized recommendations. The remote patient is equipped with wearable electrocardiogram recorder and fitness wristband that transfer health-related data to the personal mobile device. Also, the patient provides the regular questionnaire-based health log. History of past medical events, individual contraindications, etc., are received from the electronic health record. The system is composed from the set of communicating agents that provide the pieces of data and consume them to produce the recommendations.

With the advances of mobile sensors and ubiquitous presence of broadband Internet connections, the number of people using digital technologies to monitor or modify their health, tends to grow from year to year, uncovering promising opportunities for digital behaviour changes interventions (DBCIs), which was defined as digital technology-enabled services to promote behaviour changes [8]. DBCIs that are delivered to the end user through smartphone applications or wearable devices, are referred to as mobile DBCIs (mDBCIs) and are becoming increasingly useful and necessary within healthcare and wellbeing [9]. Conceptualization of hypertension treatment in terms of behaviour changes interventions is considered to be natural way in the evolution of the proposed hypertension management system. We extend the ontology of semantic representation of health-related data with behaviour-related entities and relations enabling the programming of the broader class of services for hypertensive patients.

Obviously, the expected behaviour changes may not occur despite the provided digital assistance. Therefore, the methods and tools of adherence assessment are needed to evaluate the mDBCI success. In this work, we discuss a number of sources of adherence-related data based on recent user engagement models.

The paper is organized as follows. In the Section II, an overview of the results of recent related studies is given. Section III outlines the architecture of the proposed hypertension management system and discusses the construction of the personalized recommendation service. In the Section IV, we introduce the ontology fragment for behaviour activities and changes interventions. Section V discusses the ways of adherence assessment. Section VI concludes the study.

II. Related work

Lately, many studies have been conducted at the junction of information technologies and medicine aimed at assisting the people in chronic conditions and elderlies in their independent living, in particular, in smart mobile healthcare environments.

Recent advances in wearable technology made continuous registration of the vital signs possible, providing the opportunity of the biosignal processing either on the local hardware, or in the cloud. For this reason, the efforts of researchers are mainly directed to the adoption of wearable health sensors in the healthcare services. A number of studies are devoted to continuous blood pressure measurement. In [10], the pulse transit time-based method that uses a body sensor network is proposed.

A number of electrocardiogram analysis algorithms are developed in our previous work within a CardiaCare project that is aimed at continuous monitoring of heart function in real-time and analyzing electrocardiograms on a smartphone [11], [12], [13], [14]. Within the CardiaCare project the efforts are concentrated on timely detection of rhythm abnormalities. Despite the fact that the arrhythmias are harmless in general, they can pose serious threat of complications against chronic diseases such as hypertension or diabetes. Therefore, continuous heart rhythm monitoring provides the possibility to detect the deterioration of heart function and even to save the life, and these results form the base of our current work.

The mobile application for hypertension management is presented in [15]. In this paper, the ontology-driven evidence-based mobile application for self-care is described.

In [16], the ontology for hypertension managemet is presented. The development of the ontology is aimed at the assessment of clinical decisions.

In [17], the concept of smart healthcare service was discussed. This paper significantly utilizes this concept and follows the idea of the smart service construction as the result of knowledge reasoning over a shared information. These services can effectively monitor changes in the patient's health and the environment, providing personalized recommendations as needed, without detaching him from everyday affairs [18]. Such healthcare services take into account different types of patients activity and their collaborative work, i.e., form a kind of socio-cyber-medicine system [19]. The Internet of Things (IoT) allows making components of our surroundings smart and connected.

III. The proposed solution

A. Hypertension management system overview

In the proposed hypertension management assistance system, the smart spaces approach is applied to achieve the high system scalability in IoT environments. From the one hand, the market of m-Health applications with health parameter monitoring experiences the explosive growth due to the progress of IoT technology and the advances in wearable medical devices development. For this reason, the developed system should provide a way of facile integration of the new sensor hardware. From the other hand, the development of the proposed service should support effective integration of the existing healthcare services provided by hospital information systems, in particular, the electronic health records, and to enhance them up to the level of smart services [20]. Therefore, the designed smart space-based system architecture of personalized assistance services should consider the system composed from the many components, focusing on component functionality reuse instead of reinvention.

In [17], the reference scenarios of personalized assistance and their smart space-based implementations were discussed on the example of the service aimed at the increasing the efficiency of the first aid in medical emergencies. Following the same approach, we construct the smart services for hypertensive patients.

In general, a smart space provides means for many networked devices to participate by cooperatively sharing information and other resources. Each device hosts so-called knowledge processor (KP), which acts as a software agent interacting with users, sensor equipment, and other KPs. The data produced by one KP can be shared with other KPs by means of semantic information broker (SIB). The latter provides storage for shared information collection and querying mechanism. SIB and its storage can be considered as a semantic knowledge base over multiple and dynamic data sources, similarly as it happens in the Semantic Web. That is, the knowledge base and its KPs form a computing system environment that we call a smart space.

In the proposed system, the ontology-oriented approach is adopted for representation of the shared information in machine-processible manner. An ontology describes the classes, relations, and restrictions of shared and processed

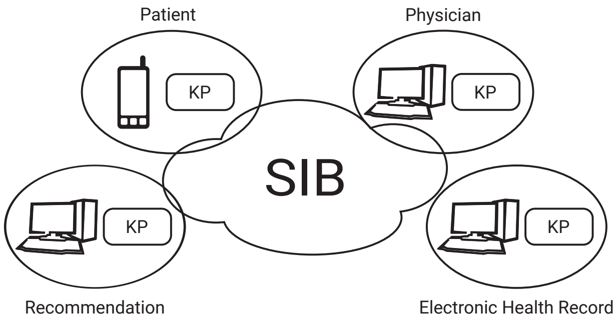

Fig. 1. Multi-agent smart hypertension management assistance system

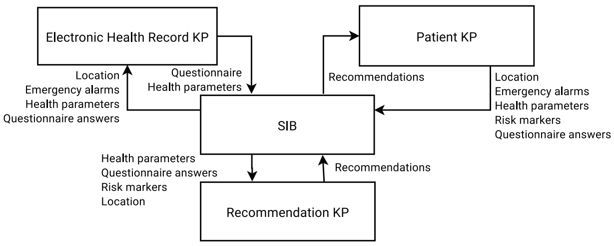

Fig. 2. Construction of the service as a cooperative activity of knowledge processors

information entities. As a result, the shared information represents a semantic network that relates a variety of heterogeneous data sources and their consumers. Data sources and consumers are represented by KPs as well as some KPs are responsible for reasoning over the data to mine and deliver the information (as services) to the end-users. The proposed multi-agent architecture of the developed system is shown in Fig. 1.

A service is constructed due to cooperative activity of KPs. The proposed system is formed by many KPs participating in the same smart space. The interaction of KPs resulting in service construction is shown in Fig. 2.

Consider a part of the scenario of hypertension management in remote patient. The patient is equipped with the personal mobile device running the KP and portable sensor devices allowing to register the ECG and physical activity. The mobile device has positioning capabilities, therefore, the location of the patient is also known.

The application shares the location, questionnaire answers and health data (along with the results of its processing) in the smart space. Patient is able to use the “panic button” also. This information becomes available to other agents. The Electronic Health Record KP updates the EHR and also publishes some data in the SIB, e.g. contraindications. Recommendation KP integrates the current health status and the data from EHR and produces recommendations to the patient.

The discussed above smart space-based hypertension assistance service provides a high level of scalability without the need of redesign of the system at whole in case of modification of individual components.

Recommendations for the patient are constructed on the base of analysis of continuously or regularly registered vital signs and health log during the treatment.

Hypertension patients management service determines trajectory of treatment and tracks its adherence. Arterial hypertension is a significant multifactorial disease with a long period of treatment. The trajectory of treatment includes changes in the patient’s lifestyle, drug and non-drug therapy. Thus, therapy takes a long time and requires patient’s self-discipline. There is a problem of a low level adherence of hypertensive patients to prevention and treatment, that is, a readiness for strict adherence to the instructions prescribed by the doctor, both when taking medication, and when changes behavior.

Basic solution of this problem is an integrated approach to managing hypertension, including the use of a background intellectual environment to monitor the patient with the help of personal recommendation service (intelligent assistants). The management of the patient includes control of various vital indicators by means of diaries. The diary should describe the patient’s life style and the chronicle of health parameters changes. From a medical point of view, the following tasks of a patient with arterial hypertension management are formed: 1) Lowering blood pressure; 2) Weight loss; 3) Regulation of admission to drug treatment; 3) Regulation of physical activity; 4) Regulation of diet and consumption of alcohol; 5) Refusal from bad habits (smoking); 6) Regulation of sleep quality; 7) Prevention of heart attack / stroke / death; 8) Protection of target organs; 9) Regulation of emotional states; 10) Decrease the influence of meteorological sensitivity; 11) Making a decision on emergency hospitalization.

The achievement of each of these tasks separately gives good results in arterial hypertension treatment. But joint efforts to achieve success in these tasks provides the most qualitative adherence to treatment. We conditionally divide the tasks into three groups: a lifestyle, measuring and medication.

The ontology was chosen for a structured presentation of patient management service. Thus the patient becomes the main element of the ontological model. The remaining elements describe the various activities of the patient. Different versions of ontology of physical activity, eating, interaction of people were found in repositories of biomedical ontologies such as BioPortal [21], Ontobee [22] and AberOWL [23].

The most suitable ones were incorporated in the proposed patient management ontology: i) FOAF: this ontology is used for the description of general information about patients since it is one of the most popular ontologies for the representation of people profiles; ii) survey questionnaire ontology (SQO): this ontology allows to construct a questionnaire with different types of answers and to structure the user responses. SQO is used to identify the patient’s feeling and health state during performing some activity; iii) semantic sensor network (ssn): the ontology describes a network of sensors and sets of measurements from them. It is attached to wearable medical and fitness devices to receive vital signals; iv) semantic mining of activity, social, and health data (smash): the ontology contains the classification of exercises and sports as well as semantic features of healthcare data and social networks; v) food ontology (fo): the ontology provides the composition data about food components or ingredients data.

Afterwards, a list of this ontologies concepts were combined together with connecting objects and the class hierarchy was defined, as it is shown in Fig. 3.

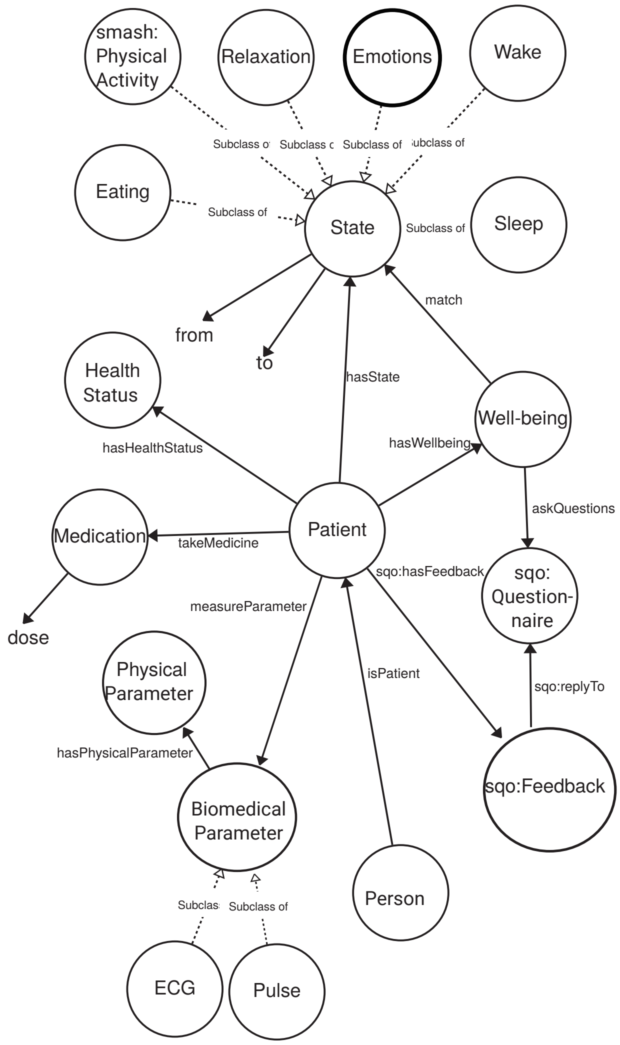

Fig. 3. Fragment of joint patient's adherence ontology

Each patient is assigned a certain trajectory of treatment. The trajectory of treatment in the form of a semantic network determines what measurements need to be carried out and with what frequency. The trajectory is part of the diary and describes the schedule of mandatory recording periods of biosignals and other measurements.

Stored in the RDF-format ontology, makes it easier to machine objects and links between them. The M3 architecture (multidevice, multivendor, multidomain) enables concept development of smart spaces to host advanced service-oriented applications. A particular open source platform is Smart-M3 [26]. Semantic information broker (SIB) is a central element. To collect information content the SIB provides an RDF-based knowledge base, which implements an RDF triplestore with support for information search and processing extensions. The RDF representation leads to interoperable information sharing.

The main task of the patient is to enter data about various types of his activity, to make measurements and do not forget to do it on time. Thus there are agents that publish data depending on their type on the client side, as it is shown in Fig. 4. For example, a Seeping Monitoring agent publishes data about retirement and awakening time. The Drug Monitoring agent publishes data on accepted medications and so on.

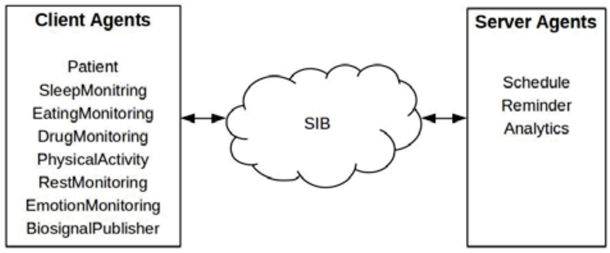

Fig. 4. Agent-based architecture of patient's adherence services

Some of these actions should be performed on schedule. The schedule is determined by the doctor together with the patient and stored on a remote server. Schedule agent delivers the current and next actions into the SIB. In the case of the presence of missed actions, the Reminder agent recalls them. Thus the patient's diary is maintained in real time mode and the adherence to treatment is monitored by the Schedule agent.

On the other hand, the purpose of keeping a diary is to find out the moments of improvement or deterioration of well-being. In this case, wearable devices are the main source of objective medical information. Biosignal data provides by Biosignal Publish agents associated with a concrete device. Set of abnormality detection algorithms is associated with each agent, depending on the signal type. The Analytics agent catches abnormalities, compares with other events that occurred during the same period. As a result of the analysis, the agent gives recommendations to the patient.

B. Gathering health-related data

The measurement can be either background or manual. With wearable devices, it is possible to obtain numerical measurements. They contain sensors, that take measurements, and support data transfer over a wireless channel (Bluetooth or WiFi). For example, an ECG monitor can transmit an ECG signal in 24/7 mode, and with a blood glucometer and a tonometer, one-time measurements are taken. Also with some periodicity it is possible to obtain measurements of laboratory tests (blood, etc.).

There are a lot of possible ECG parameters that are considered to be the cardiovascular risk markers in recent researches. These parameters are studied insufficiently and their relation with development of arterial hypertension complications is not widely confirmed.

The following ECG parameters are monitored: 1) heart rhythm disturbances such as arterial fibrillation, premature ventricular contraction and others; 2) heart blocks; 3) heart rate; 4) P wave duration; 5) P wave amplitude; 6) P wave morphology, in particular, two-phase shape; 7) PQ interval duration; 8) QT dispersion; 9) Q width; 10) R amplitude; 11) S amplitude; 12) QRS width; 13) QT duration; 14) T wave amplitude; 15) T wave alternation; 16) T wave width and "T peak-to-end" parameter; 17) ST elevation; 18) ST decrease; 19) rhythm turbulence; 20) heart rate variability.

Moreover, during the monitoring, the patients are able to record the results of independent measurements of the blood pressure. This allows to evaluate the blood pressure variability depending on many factors (ECG parameters, drug schedule, day time, etc.) between visits to the clinic.

To increase the adherence, the mobile app provides a questionnaire for the regular log of complaints and analysis of their connections with hypertension and drug treatment. At the whole, the log gives the life quality assessment that defines the adherence of the patient to the treatment plan.

The long terms of therapy together with the need of change of a lifestyle cause low adherence of the patients to arterial hypertension treatment. At the same time, development of technologies of the Internet of physical devices (IoT) promotes simplification of continuous collecting and analysis of health parameters of the patient and the auxiliary information characterizing his environment and a way of life, for making decision by the doctor on therapy change, and use of intellectual assistants—to stimulate and assess the adherence to the treatment. Emergence of similar technologies poses a number of research tasks on a joint of medicine and information technologies which are supposed to be solved within the project. The simplified questionnaire is created for the patient about a state of health covering basic complaints (including experiencing headaches, chest pain, interruptions in work of heart or heartbeat, breathing difficulties, physical activity interruptions in connection with an illness, sleep disorders, proper taking the medications, etc.).

The application allows the patient to send the alarm notification in the emergency case. The purpose is to address to the doctor timely and obtain the further guideline (e.g., call the ambulance or to take medications independently). The following list of complaints is suggested for "the alarm button": 1) intensive headaches; 2) severe dizziness; 3) nausea or vomiting; 4) sharp violation of sight; 5) severe chest pain; 6) severe shortage of air; 7) another reason.

C. Gathering lifestyle-related data

Because the lifestyle interventions, such as smoking cessation or curtailing the intake of sodium salt, calcium, magnesium and potassium, are closely related to blood pressure reducing, the accurate lifestyle habits measurement and events of interest identification are of great importance for further behaviour intervention.

Relating to lifestyle tasks describe sleep and wakefulness of the patient. The patient should write data on the time about going to bed, awakening, the quality of sleep. If he wake up at night, he marks what time it was and for what reason. Also the time of daytime sleep is described.

Wakefulness time is more filled with events. The patient should note the eating time, specifying some types of food. Periods of excitement and stress should also be noted, since they can be affected to measuring parameters. Noon intermission plays an important role for patients with hypertension. It is necessary to increase quality of blood pressure measurement and other parameters, so lying or sitting rest is also recorded in the diary.

A separate and prominent variety of activity during wakefulness is exercises. Physical activity is associated with everyday activities, such as cleaning, walking on stairs, working in the garden, and with trainings, which can include a variety of sports.

Regular medication intake plays a key role in achieving the goal of adherence to treatment. Their reception should be carried out according to the schedule and performed in strictly prescription by the doctor dosage. Also outside the schedule, the patient can take additional medications, which must be learned.

IV. Behaviour Changes Interventions

The key component of the proposed system is the intellectual assistant that provides support to the patient and motivates him or her to adhere to the prescribed treatment both in medications intake, and in lifestyle management to keep hypertension under control and for lowering blood pressure. The assistant can be represented by the only mobile app or consisted of several agents running on different devices and providing different communication modalities for efficient health care delivery. The assistant can improve health by supporting behaviours involved in disease prevention, self-management of long-term conditions, and delivery of evidence-based health care practice. Development and evaluation of effective DBCIs is challenging, we follow the recommendations for designing, evaluating, and implementing digital interventions in health care summarized in [24].

The DBCIs, provided by the hypertension management system, are described in semantic form with the Behaviour Change Technique Taxonomy, which allow to formulate the techniques in common manner with a set of "active ingredients", such as goal setting, social support or feedback on behaviour [25]. Therefore, the DBCIs are not provided by just internal rules of the assistant component. Instead, the intervention descriptions are presented in common semantic storage and can be processed, or even generated, by other involved agents. This, in turn, provides the flexibility of assistant construction, because there is no need to program certain DBCIs into the assistant code or rewrite it whenever DBCIs change.

Generating of the DBCIs outside of the assistant uncovers new dimensions in personalization, e.g. the advisory and inspiration messages can be generated in personalized manner, taking into account a range of other factors which might influence the users decision to change their lifestyle. This can be achieved, for example, by addition of extra elements to the messages to make the interaction with the system more appealing.

V. Approaches to adherence assessment

In medicine, the adherence to the treatment is usually evaluated be means of standardized questionnaire-based surveys. Without giving up this method, we propose the objective measurement-based approach to adherence assessment, realizing that the adherence concept is closely related, but not identical, to the user engagement in DBCIs.

Obviously, the term engagement cannot refer to just counts of interaction, e.g., button clicks or app openings. Measuring the frequency of contacts with intervention content should be fulfilled along with the juxtaposition of the contact with the intervention-specific outcomes, such as correspondence of medication intakes to the prescribed schedule.

Investigating engagement within DBCIs, especially mDBCIs, should be considered as a two-step process, engaging with the app and engaging with the intervention content. It is important to understand what the user is focusing on. This is challenging, as there may not be an easily measurable metric to gauge this, e.g., clicking to the button does not necessarily signify active participation.

We take into account three sources of measured engagement. Using the system regularly, the patient demonstrates To make the behaviour modification more enticing, we adopt gamification, which was defined as introducing a certain degree of game features to non-gaming behaviour. The system of achievements, or in-game non-material rewards, plays not only the role of virtual goals that increase enjoyment, but also represents an engagement level estimation.

VI. Conclusion

This paper proposed the mobile smart space-based system for the decreasing of hypertension-related risk and addressing the problem of the low adherence to the treatment among ambulatory hypertensive and prehypertensive patients. Being composed from a set of communicating agents, it provides wide capabilities of health and lifestyle-related data gathering, and outpatient assistance by means of digital behaviour changes interventions.

The system processes health data obtained with both objective measurements, such as intermittent or continuous BP and ECG measurement, etc., and subjective health measurements, provided by patient himself by means of predefined questionnaires or in a free form. Up to 20 risk markers of the cardiovascular complications in hypertensive patients that can be obtained as a result of ECG analysis on the smartphone are taken into consideration. The lifestyle-related data are also can be divided into gathered from objective sources, e.g., sleep and physical activity monitors, and self-reported.

The system provides the digital assistant aimed at supporting prescribed behaviours with a set of DBCIs. The approaches to assessment of adherence level are proposed, but should be evaluated further taking into account the specific to hypertension management DBCIs.

Acknowledgment

This research is financially supported from Russian Fund for Basic Research according to research project # 16-07-01289. The work of A. Meigal is supported by the Ministry of Education and Science of Russia within project # 17.7302.2017/6.7 of the state research assignment for 2017–2019. The work of Y. Zavyalova is supported by the Ministry of Education and Science of Russia within project # 2.5124.2017/8.9 of the basic part of state research assignment for 2017–2019. The work is implemented within the Government Program of Flagship University Development for Petrozavodsk State University in 2017–2021.

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