An In-home Medication Management Solution Based on Intelligent Packaging and Ubiquitous Sensing

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Abstract— **A healthcare solution for *medication noncompliance* problem would help to save $177 billion annually in the United States. In addition, an in-home healthcare station (IHHS) is needed to meet the rapidly increasing demands for daily monitoring with on-site diagnosis and prognosis. In this paper, an intelligent medication management system is proposed based on intelligent package and ubiquitous sensing technologies. Preventive medication management is enabled by an intelligent package sealed by Controlled Delamination Material (CDM) and controlled by RFID link. Various vital parameters are collected by wearable biomedical sensors through the short range wireless link. Onsite diagnosis and prognosis based on these health parameters are supported by the scalable architecture. Additionally, friendly human-machine interface is emphasized to make it convenient for the elderly or disabled patients. A prototype system including the hardware, embedded software, user interface, database and some intelligent packages is implemented to verify the concepts.**

Keywords-In-Home Healthcare Station; Medication Noncompliance; Wireless Sensor Network; Controlled Delamination Material; Radio Frequency Identification;

I. INTRODUCTION

Pervasive healthcare has been recognized to be the next generation form of healthcare, and distributed, patient-centric and self-managed care is emphasized as an alternative to the traditional hospitalized, staff-centric and professional-managed care [1]. Many projects and initiatives have been devoted in this strategic and promising area. Unfortunately, the concern to *prescription medication noncompliance*, which is a basic form of self-managed care, is not sufficient in these research activities [2]. A frequently cited fact is: medication noncompliance costs the United States healthcare system up to $100 billion per year, and it is the cause of approximately 11% of US annual hospitalizations [3]. It has been proven that, for the 4 most drug-spending chronic conditions (diabetes, hypertension, hypercholesterolemia, and congestive heart failure), hospitalization rates are significantly lower for patients with higher medication compliance [4]. More startling facts are listed in a report from the National Council on Patient Information and Education (NCPIE) in 2007 [5]: only about 50% of American patients typically take their medicines as prescribed, resulting in approximately $177 billion annually in direct and indirect costs to the U.S. economy.

To establish a multidisciplinary approach to compliance education and management has been pointed out in this 10-step action plan [5]. One solution for this purpose from traditional industry is the One Dose Packaging [6], but it just makes medication more convenient for patients rather than improves the *compliance* or prevent from the *noncompliance* directly. Noncompliance detecting and recording was introduced by a prototype of Smart Medical Refrigerator [7], a microchip powered tablet package [8] and a Smart Dose Reminder [9]. But they are mainly used as *afterward checking measure* instead of *preventive measure*. Their complicate operations are only usable for a well-trained caregiver instead of patient, teenager, elderly, and disabled.

At the same time, rapidly increasing demands of daily monitoring is driving homecare solutions to integrate more and more sensing and data processing capacities with on-site diagnosis and prognosis. For example, tri-axis accelerometer, electrocardiogram (ECG), blood pressure, blood oxygen saturation (SpO2), respiration oxygen saturation, blood sugar concentration, body temperature are monitored on 24/7 basis [10-14]. So a powerful system is needed not only to address the medication noncompliance but also to be used as a generic in-home healthcare station (IHHS) in everybody's home.

In this paper, an in-home medication management and healthcare system is proposed based on Radio Frequency Identification (RFID) and ubiquitous sensing technologies. Preventive medication management is enabled by an intelligent packaging sealed by Controlled Delamination Material (CDM) and controlled by RFID link. Various vital parameters are collected by wearable biomedical sensors through wireless link. Onsite diagnosis and prognosis for these health parameters are supported by the scalable architecture. Additionally, friendly human-machine interface is emphasized to make it usable for the elderly, disabled and patients. A prototype system including the hardware, embedded software, user interface, database and some intelligent packages is implemented to verify the system concepts. The experimental results confirm the feasibility of the proposed solution.

The rest of this paper is organized as follows. The system functionality and architecture are given in section II. Detailed hardware and software implementation is described in section III. Experimental results are discussed in section IV. Section V concludes the paper and discusses open issues.

II. System Architecture

A. Application Scenario

A typical application scenario of the proposed system is illustrated in Figure 1. The centre of the system is a powerful intelligent medicine box (iMedBox), which works not only as a traditional in-home medicine container (such as a drawer of cabinet, a thermostat or an icebox), but also as a "*medication inspector*", and an "*onsite examiner*" in daily monitoring. At one end, it is linked to public area (e.g. the hospital, the medicine supply chain and the emergency help center) through wireless internet. At another end, it controls a suit of intelligent medicine packages (iPackage) and a suit of wearable biomedical sensor tags (iTag) through RFID and wireless biomedical sensor network (WBSN) respectively. More information is available in our previous work [16].

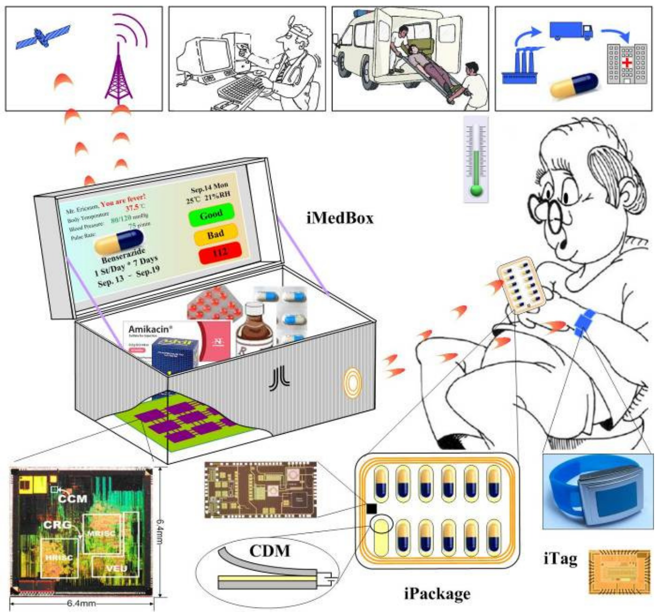

Figure 1 Application Scenario

B. Intelligent Preventive Medication

Compared to existing solutions, preventive strategies to address medication noncompliance are supported in a way of nip-in-the-bud by reminding, recording, preventing, diagnosis and prognosis and supporting, which have been identified to be more effective [5]. It includes the following functionalities.

Medicine Inventory: The iMedBox can register, record, query and statistic all medicine utilities automatically by reading the RFID tags on them since the medicines are taken home.

Medication Reminding: The iMedBox can download and parsed the prescription automatically and it can send a reminder to the patient e.g. by flashing on the screen, loud sound or music from the speakers, flashing of lights, etc.

Noncompliance Recording: All of the patient's medication related activities (e.g. opening the box, taking a dose, forgetting to take a dose, destroying some medicines by mistake, throwing some medicines away, etc.) are detected and recorded.

Noncompliance Preventing: patient can not by hand open the iPackage sealed by tight CDM films without opening command from iMedBox observing the prescription. Thus advanced and excessive medication is entirely prohibited.

C. Onsite Diagnosis Framework

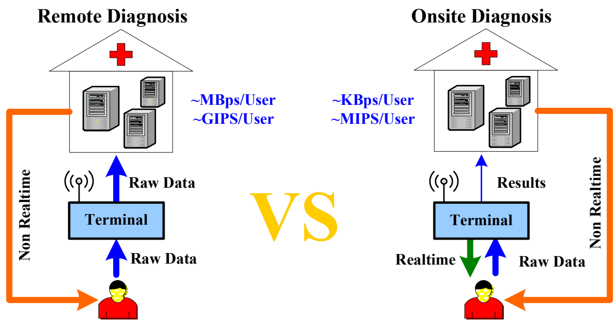

Figure 2 Onsite diagnosis vs. remote diagnosis

There are mainly two kinds of frameworks in pervasive healthcare systems (Figure 2). In Remote Diagnosis Framework, the raw date collected by onsite terminal is transmitted directly to the server and a non-real-time and long term feedback is given to the user according to analysis results. Contrary, in Onsite Diagnosis Framework, preprocessing is performed in the onsite terminal and only results (instead of raw data) are transmitted to the server. In this way, both the traffic load between terminal and server and the computation load in the server are reduced significantly. This makes the latter solution more effective and efficient, because the data transmission and processing in Remote Diagnosis Framework would overwhelm the communication system and resources in server when it is widely adopted. Furthermore, the onsite terminal could give users feedback at first time and first place, which is very important for some urgent situations such as acute myocardial infarction.

So we adopt the Onsite Diagnosis Framework to design the proposed system. In iMedBox, a suit of basic diagnosis and prognosis examinations can be performed in the software. Feasible algorithms are becoming available during the efforts in many research activities, e.g. human movement classification and detection based on tri-axial acceleration, ECG signal compression based on discrete wavelet transformation, heart premature detection based on ECG signal classification [11-14].

D. System Architecture Diagram

As shown in Figure 3, multiple wireless links are integrated in iMedBox. User friendly human-machine interfaces (HMI) are provided including a LCD displayer, a touch screen, a camera, speakers, a microphone, shining LED lamps and vibrators.

- Wireless internet link: includes WiFi and/or GPRS/3G communication stacks, system security, data base access, web server for data shearing.
- Global Positioning System (GPS) link: is very useful to deliver emergency treatment when users are away from home.

- WBSN link: includes start-topology network configuration and data collection.
- RFID link: includes medicine inventory management, CDM controlling and medication compliance detection.

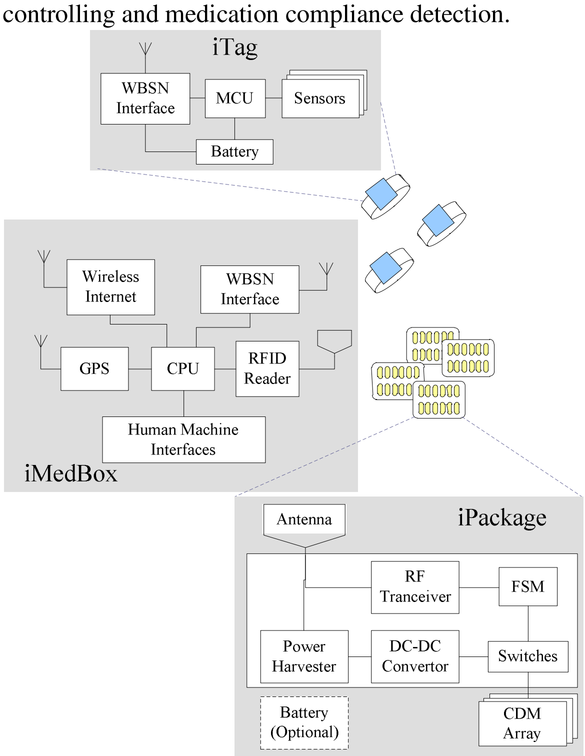

Figure 3 System Architecture

In the iPackage, a significant difference comparing to traditional RFID attached packages is that, an array of CDM films and corresponding control circuits are added. The CDM film is a 3-layer foil composed of an aluminum bottom layer, an aluminum top layer and an adhesive middle layer made of electrochemical epoxy. When the voltage subjected between the bottom layer and top layer is higher than a particular threshold, namely Delamination Voltage (V_d), the electrochemical reaction is triggered in the middle layer. Furthermore if the voltage maintains longer than a particular time, namely Delamination Time (T_d), the epoxy layer is destroyed and delaminated. V_d and T_d are both distinct parameters determined by the formula and processing when the material is manufactured [15].

The distinct characteristics of CDM are used to perform noncompliance preventing function in a nip-in-the-bud way. The iPackage sealed with a CDM film can be opened by the iMedBox by sending an OPEN command to the microchip in iPackage. And on the contrary, it can not be opened by the patient without the OPEN command because the adhesive is too tight to human's hands. Tablet level controlling can be achieved by addressing each CDM film in the command, so that each dose could be exactly observed. As a passive solution, power harvesting from near field magnetic resonance is an available method to provide energy needed by the electrochemical reaction during delamination. Or as an alternative, a printed battery could be manufactured along with the package to make a self-powered solution. This has been proven by experimental results in the next sections.

The iTag is of mainstream architecture in WBSN, which comprises a WBSN interface, a low power MCU, a suit of biomedical sensors and a battery. The battery-powered architecture has significant advantages in communication distance and sensing capacity comparing to passive of self-powered ones.

III. Prototype of Intelligent Package

A. *Prototype of CDM and intelligent package*

To analyze and evaluate the CDM material for iPackage, we made a dedicated demonstration board including a near-field resonance coil, a resonance driver chip, an MCU, two button batteries, a DC-DC converter, a power switch and a piece of CDM film (Figure 4). In this step, the main power source is the button batteries and the near-field resonance coil is just for control commands. The DC-DC converter multiplies 3V battery voltage to 30V to the CDM if an OPEN command is received from the coil. More information is available in our previous work [17].

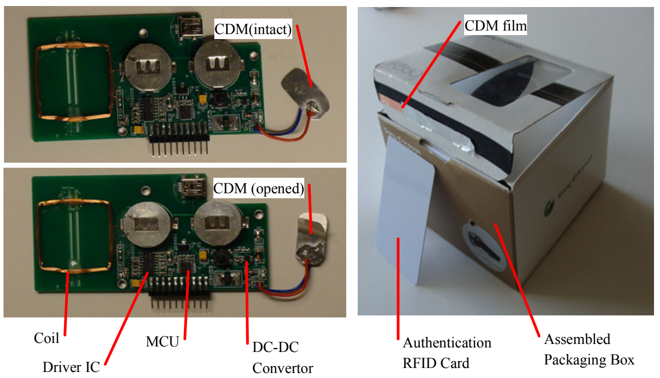

Figure 4 Prototypes of CDM (left) and assembled intelligent package (right)

B. *Setup of experiments for CDM charactorization*

The main task of CDM characterization is to evaluate the energy and power needed to open a unit area of CDM film, where the Delamination Voltage (V_d), Delamination Maximum Current (I_d), Delamination Time (T_d), Delamination Power (P_d) and Energy expense (E_d) are measured and calculated.

As mentioned in the previous study [15], CDM will quickly open if it is added a voltage in 10-50V range, and if some environment conditions affect CDM electrochemical characteristics. The following tests are performed at a temperature round 22°-25° and a relative humidity of 30%-37%, within the safety range of 36V for human. To formalize the test results, the size of test CDM pieces is set to 1cm^2 because the size of film is almost unrelated with opening time [15]. During the whole delamination period, current through the CDM film is measured by a 180 Ohm serial resister.

C. *Delamination Behavior*

To monitor the delamination behavior of CDM, we apply a 30V DC power source to a 1cm^2 CDM film. As shown in

Figure 10, in the beginning, the current reaches its maximum value 0.95 mA/cm2 (I_d) in a few seconds. When holding power source voltage for about ten seconds, the current drops down significantly. After 90 seconds, the current is reduced by over 90%, and the diminution turns to slow. At this moment, the CDM film is so weak that just a slight tough can make it peel off. But as we can see in the last 60 seconds, without any external force, the current through the material is very small which is infinitely close to zero but never equal to zero.

In order to standardize the delamination behavior, a static shear force is added to one surface of the CDM film by hanging a mall weight. When the adhesive strength cannot afford the weight, the CDM film is disbanded immediately. The current at that moment is called Turnoff Current which signifies the material is delaminated. And T_d is defined as the interval from power supply is applied on the surface till the current reaches the Turnoff Current in a current curve.

D. *Impact of Power Source Dutycycle*

Four duty cycles of a 100 KHz and 30V power source are applied to a 1cm^2 CDM film respectively. When duty cycle of power source increases from 20% to 100%, the T_d decreases disproportionately (Figure 5).

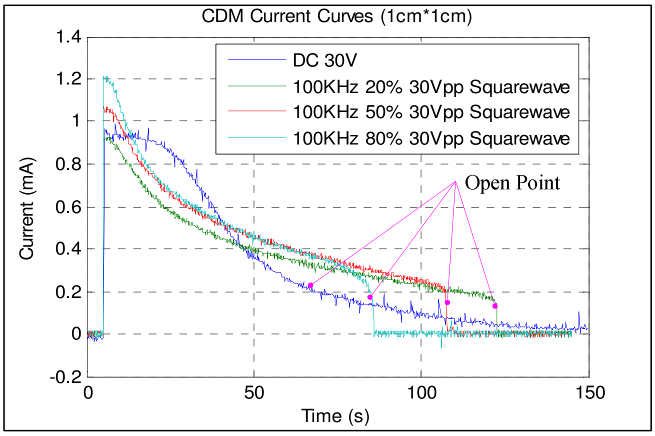

Figure 5 Impact of Power Source Duty Cycle

E. *Impact of Power Source Voltage*

The current through the material under different power source voltages from 5V DC up to 30V DC are plotted in Figure 6. When the power supply is lower than 5V, the CDM will not open within 2 minutes without any large external shear force. When the voltage increases from 5V to 30V, the T_d decreases significantly and disproportionately.

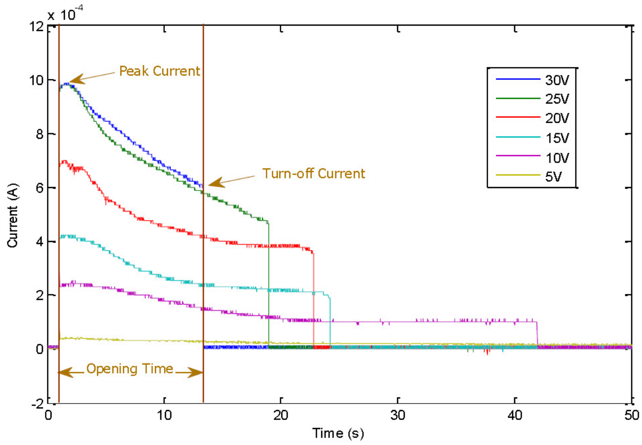

Figure 6 Impact of Power Source Voltage

F. *Impact of Material Process Variety*

For CDM pieces at different position from the same reel, the difference of T_d is neglidgible. But the difference between pieces from different reels is larger according to measurement results of 4 pieces from 4 different reels in Figure 7. The main reason is that the difference in the material process and quality from reel to reel is larger than that from region to region in one reel.

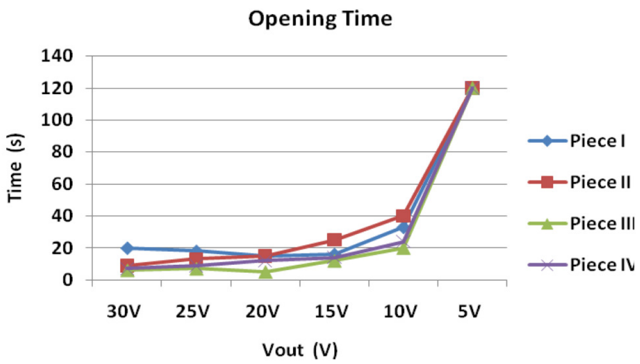

Figure 7 Impact of Material Process Variety

G. *CDM Characterization Conclusion*

From the results described above, we can make the following conclusions:

1) I_d is at the order of 1mA/cm2

2) V_d is at the order of 30V

3) T_d is at the order of 100s

4) P_d is at the order of 30mW/cm2 (=1mA/cm2*30V)

5) E_d is at the order of 3J/cm2 (=30mW/cm2*100s)

This implies that a printed thin-film battery with 3.3mAh capacitance is sufficient to open up to 12 tablets sealed with 1cm^2 CDM film for each. This is a typical application case in practical tablet packages. But one important factor should be taken into considerations: most of printed batteries have a large internal resistance which will decrease the peak current and prolong the T_d. As an alternative, available wireless power transmission technology is sufficient to provide this energy. So, it is feasible to use the CDM material to realize the proposed intelligent package.

IV. PROTOTYPE OF INTELLIGENT MEDICINE BOX

A. iMedBox Prototype

The 2nd version of prototype system of iMedBox is implemented based on the FriendlyARM Mini 6410 Single-Board Computer (Figure 8). The main CPU is S3C6410 processor from Samsung Semiconductor which integrates an ARM11 CPU running up to 667MHz. The wireless internet interface is based on Marvell's W8686 IEEE802.11g module with a thin film 2.4GHz antenna. A 7 inches TFT-LCD and a full-sized touch screen is integrated as the main human-machine interface. A UHF RFID reader module is used combining with a flatten ceramic antenna.

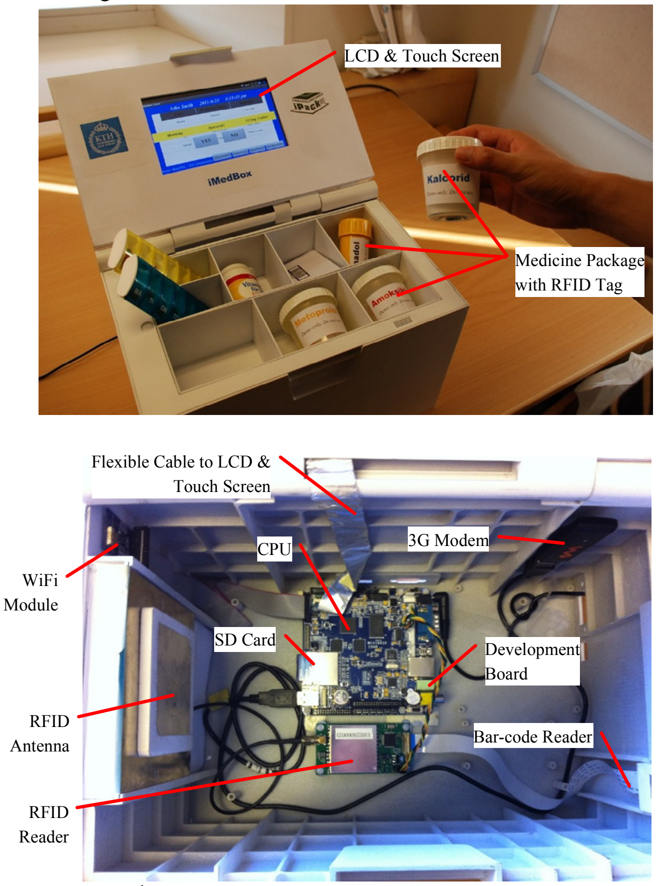

Figure 8 The 2nd version of iMedBox prototype (top) and inside view (bottom)

B. User Interface Software

The Google Android2.1 operation system is ported to the platform and demonstration software is developed in Java. In the main window of the demonstration software (Figure 9), Patient's Information, Prescription Details, Medication Records, Date and Time, Doctor Information, and Feedback buttons are displayed with highlight and large font size, which makes them clearer for users with poor eyesight.

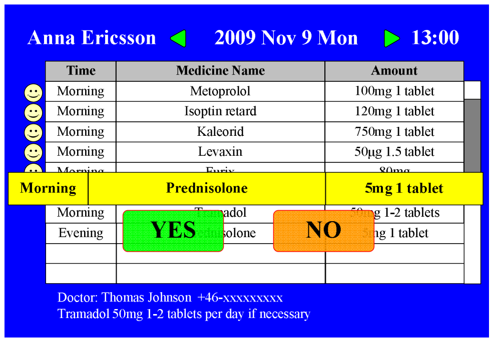

Figure 9 Sample Page of User Interface

C. Medication Database

The primary entities (tables) of the Medication Database (MDB) and relations among them are shown in Figure 10 where all prescription and medication information is well organized. Correctly handling of the DoseList table in MDB is the core of the database system. Firstly, when a new prescription is issued in hospital, corresponding records are added in by dispatching one prescription into multiple dose lists. Secondly, when user opens the iMedBox, a timely dose list that should be taken today is retrieved. Thirdly, medications records will be updated to the MDB no matter if the doses are taken correctly or not. Example procedure and codes in Structured Query Language (SQL) are shown in Figure 11.

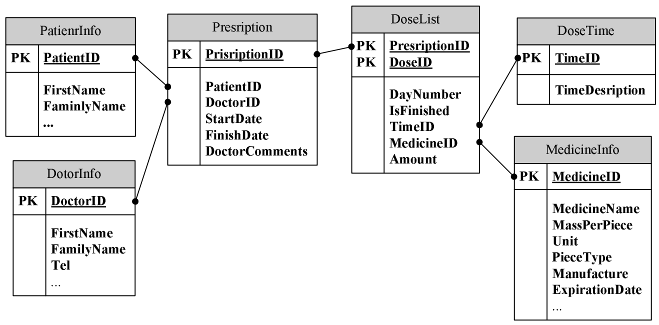

Figure 10 Key Tables in Medication Database

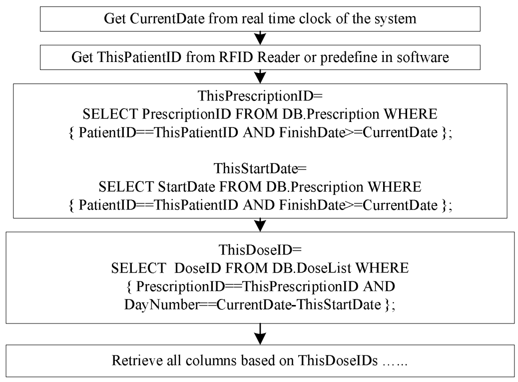

Figure 11 Procedure of Medication Database Query

D. Demonstration

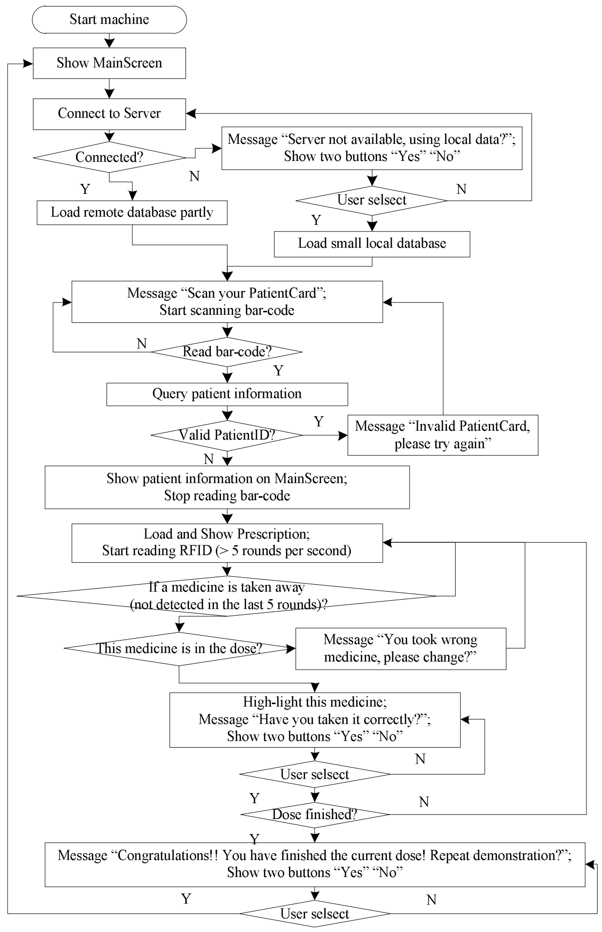

Figure 12 Procedure of Medication Database Query

Some field trials have been carried out in nursing centers and elderly houses in Blekinge, Sweden. The demonstration flow is shown in Figure 12. The system concepts have been confirmed by the positive feedback. The medication reminding and recording functions can significantly improve the medication compliance, especially for elderly patients.

V. CONCLUSION

In this paper, a pervasive and preventive healthcare solution addressing the medication noncompliance problem is proposed. A prototype system is implemented which confirms the feasibility of the presented intelligent package.

At the next step, on-site algorithms will be implemented as well as data collection through open market available WBSN devices. Integrating the CDM film with wireless power transmission and RFID tag onto one flexible substrate is another interesting task. The user experience performances and user interfaces will be further tested and optimized in field trials in the patients with chronic diseases.

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