A Mobile Monitoring System of Blood Pressure for Underserved in China by Information and Communication Technology Service

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***Abstract*—High blood pressure (BP, hypertension) is a leading chronic condition in China and has become the main risk factor for many high-risk diseases, such as heart attacks. However, the platform for chronic disease measurement and management is still lacking, especially for underserved Chinese. To achieve the early diagnosis of hypertension, one BP monitoring system has been designed. The proposed design consists of three main parts: user domain, server domain, and channel domain. All three units and their materialization, validation tests on reliability, and usability are described in this paper, and the conclusion is that the current design concept is feasible and the system can be developed toward sufficient reliability and affordability with further optimization. This idea might also be extended into one platform for other physiological signals, such as blood sugar and ECG.**

***Index Terms*—Blood pressure (BP), community healthcare center (CHC), measurement, short messaging service (SMS).**

I. Introduction

BLOOD pressure (BP) monitoring, as practiced in the developed world, is an expensive proposition for most Chinese. There are more than 100 million hypertension patients in China, but only 36% are aware of their condition (16% in rural areas) [1]. Their high BP, therefore, only becomes known to them when they are confronted with serious diseases, such as atherosclerotic cardiovascular disease, which may result from hypertension. Currently, people in China have unmet and growing needs, such as BP diagnosis, monitoring, and electrical records management. However, they are still facing several challenges; for instance, lack of cheap intelligent home-care BP measurement devices, or having to travel long distances for medical treatment because of limited physical infrastructure, or an unbalanced distribution of medical resources.

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There are a substantial number of existing initiatives outside China focusing on BP, but some of the elements are lacking, and certainly, they are not completely suitable in the Chinese context. The CodeBlue Initiative by Harvard University [2], MARSIAN by CNRS [3], [4], and Lifeguild by NASA [5] focus only on technical innovation and do not include innovating implementation procedures into the societal context. Projects from industrial companies, such as Lifeminder by Toshiba [6], provide too much physiological data, which is difficult to process by the unskilled care workers of the Community Healthcare Centers (CHC), who lack the skills and knowledge of those workers employed in similar roles in developed countries, and MyHeart by Philips [7] targets only wealth users. MobiHealth by Ericsson [8] only focuses on mobile technologies (not on the networks and services).

As a result, a new system, temporarily named "iCare-SHU," is proposed in this paper, which is designed to fit into the current Chinese local context. The basic idea is that rural patients can measure their BP values by themselves and automatically send them to the CHC, while community doctors at the CHC are in charge of these BP records and give the feedback to rural patients. Also, more expert medical support is provided from a distance by the specialist hospital in the city through the Internet service. To identify design objectives, user requirements are considered as the starting point. Considerable user research has been carried out in the period from 2005 to 2006 [9], [10], e.g., contextual requirements and the assessment of maximum costs for this type of service. Table I shows problems, design objectives, and proposed solutions for the system functional design.

Until now, the first-generation "iCare-SHU" system (e.g., the wrist measurement device, interfaces, the network, and the server) was prototyped to demonstrate our design concept. In this paper, we will introduce the system design, its evaluation in the laboratory and the field. Finally, we will conclude that the concept is feasible, but more studies will be given for developing the second-generation "iCare-SHU" system and service validation. Other biosignals, such as blood sugar and ECG, might also be added into this system in the future.

II. System Description

Based on user requirements, as summarized in Table I, we proposed the first-generation "iCare-SHU" systemic framework, which includes the following three main domains (see Fig. 1).

TABLE I
PROBLEMS, DESIGN OBJECTIVES, AND PROPOSED SOLUTIONS FOR THE NEW SYSTEM

Problems	Design objectives	Proposed solutions
Existing commercial electrical BP measurement devices are too expensive and there is a lack of communication between patients and doctors	Low cost and sustainable portable measurement device, reliable and convenient	Wireless measurement device to wear around wrist
Existing commercial electrical BP measurement devices are too complex for underserved Chinese	User-friendly self operation terminals, automatic detection	Intelligent automatic detection sensor, automatic control and measurement device
A continuous awareness, required for self monitoring of BP, is still lacking in Chinese patients	Patientsí involvement into the monitoring process	SMS platform, voice alarming system
Lack of hypertension data management for medical staff	User-friendly management system based on Information and Communication system	A platform with database support for data management

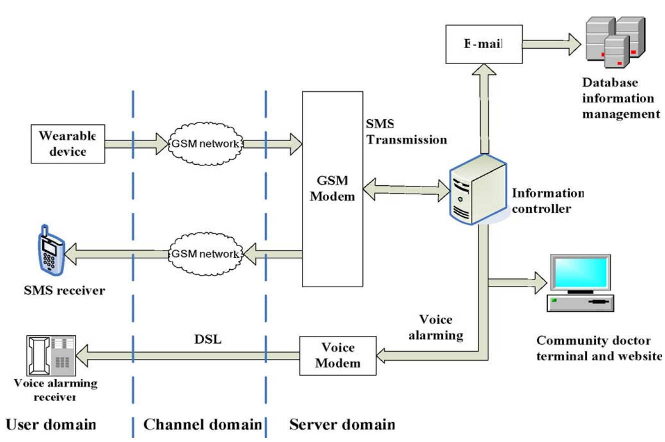


Fig. 1. Platform framework for “iCare-SHU” system.

1) *User domain:* It includes wearable measurement devices and information receiver terminals. Patients are able to measure BP values independently, by wearable wrist devices. The data will be automatically transferred to a data server in CHC/point (P) real time. It will be then analyzed by the server and, where necessary, a short messaging service (SMS) alarm will be sent to the user’s mobile phone or by voice alarm call to a fixed phone number. Finally, the data will be stored in the server for manual analysis by the caregiver.
2) *Channel domain:* Global system for mobile communications (GSM) network has been chosen as the wireless transmission channel and digital subscriber line (DSL) has been chosen as the wire network.
3) *Server domain:* The medical staff in the CHC is in charge of BP data management and analysis. Both communication modem and database are designed into this domain.

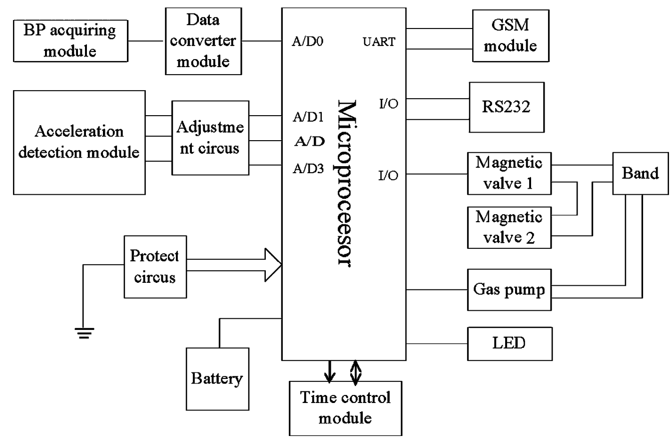


Fig. 2. Design of the wearable measurement device.

At the same time, the server can be connected to specialists in large hospitals through existing Internets and specialists (physicians with MD degree and more than five years clinic experience) will give advice if needed.

By using this system, BP measurements are automatically delivered to the server at certain times throughout the day, depending on the patient’s situation. Doctors in CHCs can observe data from the server and analyze results (such as BP trend analysis) for every patient through dedicated (to be developed) software. If any medical problem occurs, e.g., when the BP level rises to problematic levels, feedback will be sent to both user terminals (patients) and database server.

A. User Domain

The basic function of user domain is to collect BP information automatically, sending BP information, and receiving alarm signals. In the first-generation “iCare-SHU” system, the user domain consists of three separate components: a wearable measurement device, SMS receiving terminals, such as mobile phones, and a voice alarm receiver, such as a fixed land line. In this project, main investigations in this section are concentrated on redesigning wearable measurement devices. A user manual has also been developed to guide users.

1) Wearable BP Measurement Device:

a) Design of wrist measurement device: The chosen technology for the wrist device is oscillometric technique [11]. The study and clinical implementation of wrist measurement of BP with oscillometric technique has lasted for more than 20 years [12]–[14]. Therefore, it has proven to be sufficiently reliable for preventative and monitoring purposes for patients at home [15]–[17]. Also, it is considered to be one of the major methodologies in the design of electronic BP measurement devices [18].

Fig. 2 shows the design of the measurement device, which consists of several modules: BP-signals-acquiring module, gas-pump module, acceleration-detection module, data-converter module, microprocessor module, time-control module, SMS-sender module, etc.

Fig. 3. Prototype of wearable measurement device (first generation).

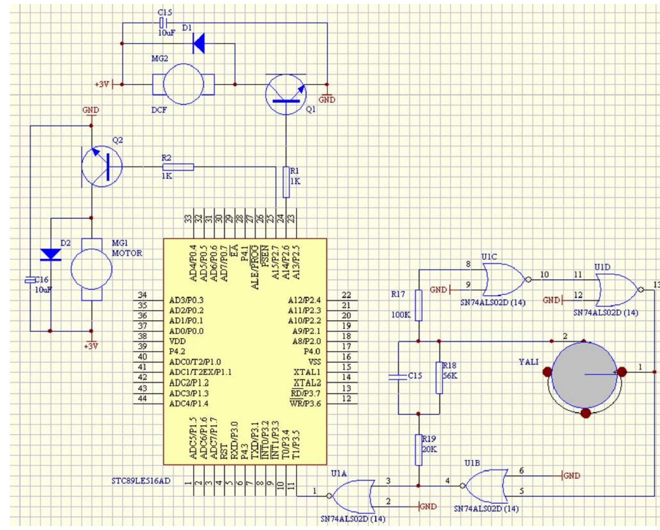


Fig. 4. Design of the BP-acquiring module.

The work cycle (data cycle) of this device is described as follows: most of the time, this device will be working under system-sleeping status, which saves battery life. The time-control module sends a signal to the microprocessor at a certain fixed time (for instance, 8:00 A.M., 10:00 A.M., 14:00 P.M., 16:00 P.M., and 18:00 P.M.), according to common BP monitoring practice. The times can be scheduled according to individual requirements. As soon as the signal is received, the device shifts itself from sleeping to working mode. First, the current bodily activity of the patient is assessed. The user might be sitting, lying, walking, or running, etc., while during BP measurements, not much activity is allowed. The acceleration-detection module will detect acceleration and decide whether a measurement at this time is permitted. The result is sent to the microprocessor module. Second, if the measuring is permitted, the BP-signal-acquiring module will be activated. The gas will be driven in and out through a gas pump on the wrist and pressure signals are retrieved. The driving-in speed is sharp (within 5–6 s) and the driving-out speed is slow (>30 s). Third, the pressure signals will be converted into electrical signals through the data-converter module and transmitted into the microprocessor. Finally, the electrical BP value will be sent through SMS-sender module to the server. The interface is user friendly. Patients are able to operate this device with one button and follow basic measurement manuals (e.g., keep the wrists at the same height with the hearts).

Two chargeable AA batteries (BL-5 C 1050 mA) provide sufficient power to support the unit works for more than three days. The current prototype of the wearable measurement device is shown in Fig. 3. In the next design, there will be a reduction in size to that of a watch size for comfort.

b) BP-acquiring module: Because this system should be reliable and cheap, we chose STC89lE516AD as the microprocessor of the measurement device, which is a low-cost single-chip. The design of the BP-acquiring module is described in Fig. 4, where the *RC* peripheral circuit works to protect this system and control the current.

One innovation in this module is the design of a simplified BP measurement algorithm, which reduces the calculation loads on the microprocessor. Since the calculation ability of the microprocessor is low while the accuracy must be kept, the most obvious solution is to simplify the algorithm. The proposed algorithm is named as "P5" in this case, which is based on Pulsus Alternans algorithm [19]. (According to Geddes [19], only two amplitude values (AVs) of three: systolic pressure value (SP), diastolic pressure value (DP), and mean pressure value (MP) should be measured and the rest one can be calculated through computation.) Fig. 5 describes the flowchart of computed process about "P5" algorithm, which includes the following four major phases: 1) record all peak values and floor values within a heart beat cycle; 2) the AV of BP wavelets within the cycle are recorded and memorized; 3) find and record the maximum of AV (AV0) through comparison, and MP = AV0 at this moment; and 4) find SP and DP through comparing AVs, which is close to K_s and K_d. After a 20 groups' comparison experiment, we found that $K_d = 0.71$ for our device and DP could be found in the next nine wavelets. Therefore, we chose the collection of MP and DP, while SP can be computed. The definition of "P5" is due to only five memory units being needed in this algorithm and 40-B memory space is required in practice. This means that 8 bits microchip is enough to support all calculations. The research on "P5" is still ongoing and optimization will be given in the future.

c) Acceleration-detection module: Compared with existing wrist BP measurement devices in the market such as Omron, one invention of ours is that we added an acceleration-detection module, which helps to decide the users' body status automatically.

In daily use, physical activity is the general reason resulting in errors during BP measurement [20]. The difference between a resting mode, such as sleeping or sitting and an active mode, such as running or walking, is obvious, especially for wrist measurement [20]. The BP value will be higher because of movement. Therefore, an acceleration-detection module was designed, which can assess current bodily activity. The decision

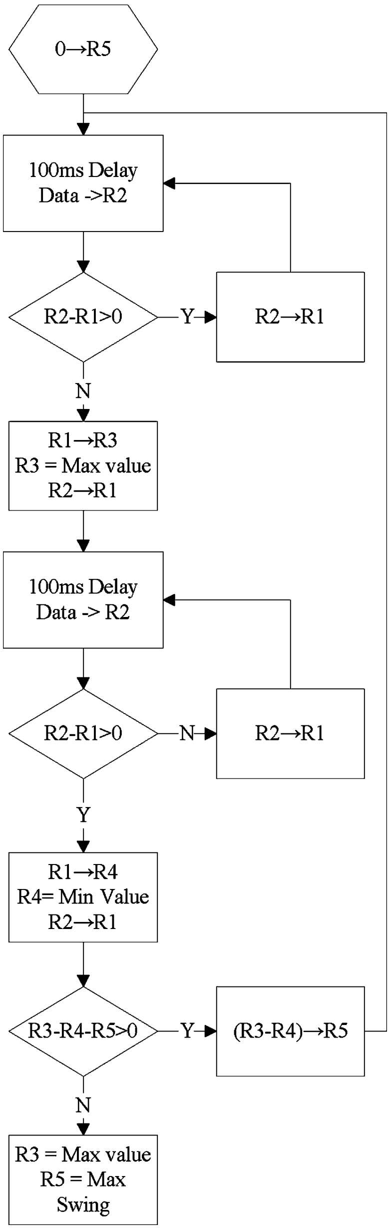


Fig. 5. Flowchart of optimization algorithm for SP, DP, and MP calculation (first generation).

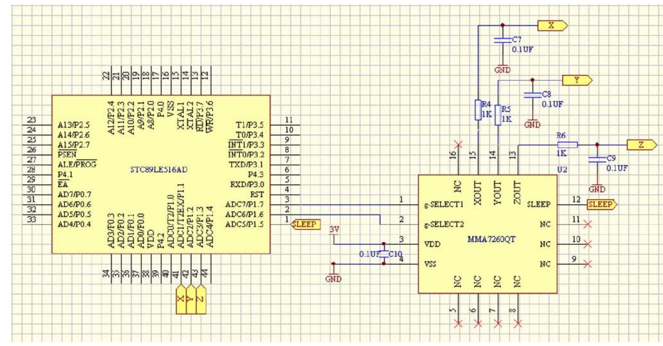


Fig. 6. Architecture of acceleration-detection module.

TABLE II
ACTION DESCRIPTION FOR EXPERIMENT ABOUT ACCELERATION-DETECTION MODULE TESTS

Item	Posture	Action description
1	Sit	Sit，put hands on the knee，keep body straight，without backrest
2		Sit，put hands on the knee，keep body straight，with backrest
3		Sit，put hands on the desk，keep body straight，without backrest
4		Sit，put hands on the desk，keep body straight，with backrest
5		Sit on a bus seat
6	Lie	Lie low，put two hands beside both sides of the body
7		Lie flank，put two hands beside the top side of the body
8	Stand	Stand straight，put two hands beside both sides of the body
9		Stand straight, raise hands to heart position
10		Stand straight，take bags in the both hands
11	Limited exercise	Writing and typing in the office while seated
12	Exercise	Walk（80-90steps/s）
13		Scale（2steps/s）
14		Canter（2.5meter/s）
15		Mop or sweep the floor
16		Shadowboxing

of this module can advise patients whether current status is suitable for BP measurement.

The core of acceleration-detection module is a 3-D acceleration sensor. Here, we chose MMA7260 chip (manufactured by Freescale, USA, low cost in the market) as the sensor, and a self-designed data-acquiring module has been used to support the acceleration sensor. Fig. 6 shows the architecture of this model.

To make the threshold of the acceleration-detection sensor to help, the chip decide the level of physical activity of users, six student volunteers were invited to take part in an experiment. They were asked to have a rest for 15 min first, wear the sensor and a commercial wrist measurement device (Omron HEM-6011), second, keep the same height between device and heart carefully, and then, carry out actions with the guide. Sixteen activities had to be performed by these students with an interval of 3 min between each step. Table II illustrates all 16 activities derived from the daily life of a typical Chinese person. These were divided into five groups: sit, lie, stand, limited exercise, and exercise.

The participants did the prescribed actions while acceleration was measured by the acceleration sensor on the wrist. Immediately following the end of every activity block, the BP was measured by the Omron device.

The aim of the tests was to identify the digital threshold of the acceleration-detection sensor as a decision support for the microprocessor. This detection value is a voltage value, and then, it will be input into the microprocessor module directly as

TABLE III
LIMITS OF AGREEMENT FOR THE ACCELERATION MODULE (IN VOLTS)

Direction	SP	DP
XMAX	1.75	1.80
XMIN	1.25	1.28
YMAX	1.94	2.00
YMIN	1.48	1.55
ZMAX	2.40	2.40
ZMIN	2.12	2.08
XMAX	1.75	1.80
XMIN	1.25	1.28

the additional signals. Six groups' experiments actually helped us to find the threshold values in each direction *X*, *Y*, and *Z*. After the Bland—Altman analysis [21] based on action status and just action-finishing status, the limits of agreement (the threshold values in each direction) are described in Table III. The threshold values are simplified as $X_{\max} = 1.75$ V, $Y_{\max} = 1.94$ V, and $Z_{\max} = 2.4$ V, while as acceleration $X_{\max} = 0.15$ g, $Y_{\max} = 0.388$ g, and $Z_{\max} = 0.938$ g. These values were programmed into the chip.

2) Other Modules: Other modules within the user domain are mainly purchased from the market, with the most important criterion: low cost. For instance, the microprocessor module is based on STC89C516AD signal-chip computer; the acceleration module is based on MMA7260; the clock module is based on DS17887 from Maxim; the data-converter module is based on MAX3241E; and GSM module is based on TC35 module from Siemens.

Currently, the user-friendly interface design for SMS receiving terminal (mobile phone, personal digital assistant (PDA), iphone, etc.) is still being developed and the next steps is to devote more attention to human–computer interaction.

B. Channel Domain

Since public communication networks in China are advanced (e.g., GSM network covers 95% of China by China Mobile), the study for channel domain in this project is to develop a low-cost, real-time GSM sender and receiver terminal, which could be integrated into the server.

The functional development of channel domain includes four parts: SMS reception from wearable device, SMS sending to SMS receiver terminal (mobile phone), voice alarming sending to users, and E-mail sending to the server. The work flowchart of this domain is described in Fig. 7. At the beginning, the module will decide the purpose, and accordingly, different processes (including SMS encryption/decryption process if need) will be carried out. Finally, all information is stored in the database.

The rule of SMS encryption/decryption has been shown in Fig. 8. In the coding sessions, coding head ABCD demonstrates the encoding rule and it means that this message is special for BP information transmission and will be sent to a special SMS server in CHC/P; 12345678901 means the sender information, which can be a mobile number; YYYYMMDDHH means the recording time of this series; 120/80 means the BP values (SP/DP); coding end EF is the blank coding for adding more useful information in future (such as heart rate). And the default status is 00.

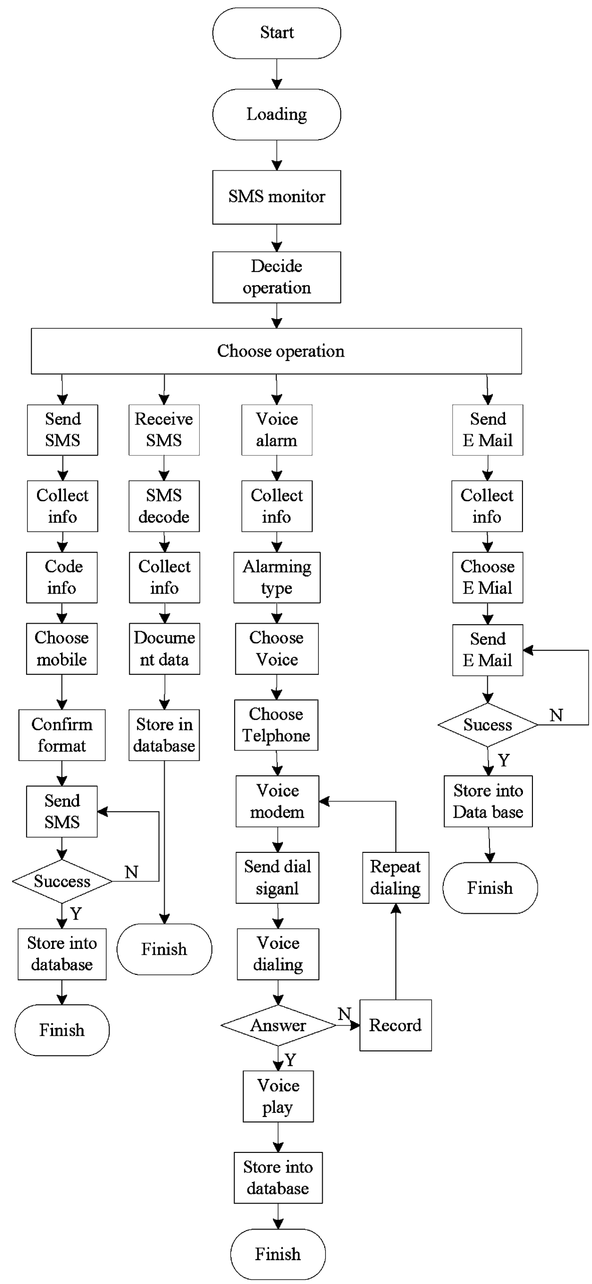


Fig. 7. Work flowchart for channel domain.

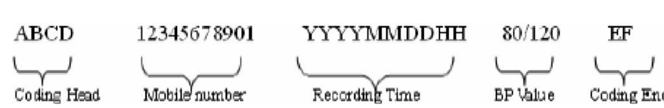


Fig. 8. Encoding series of SMS for the server.

The hardware of this module is based on TC35 wireless module (Siemens) and the program is based on AT order set, which is one type of general application programming interface (API) methods. The voice signal is built up through TP-Link 56K voice modem and the transmission is based on ITU-T V.90/X2/56k protocol. Current achievement is that the voice signals can be

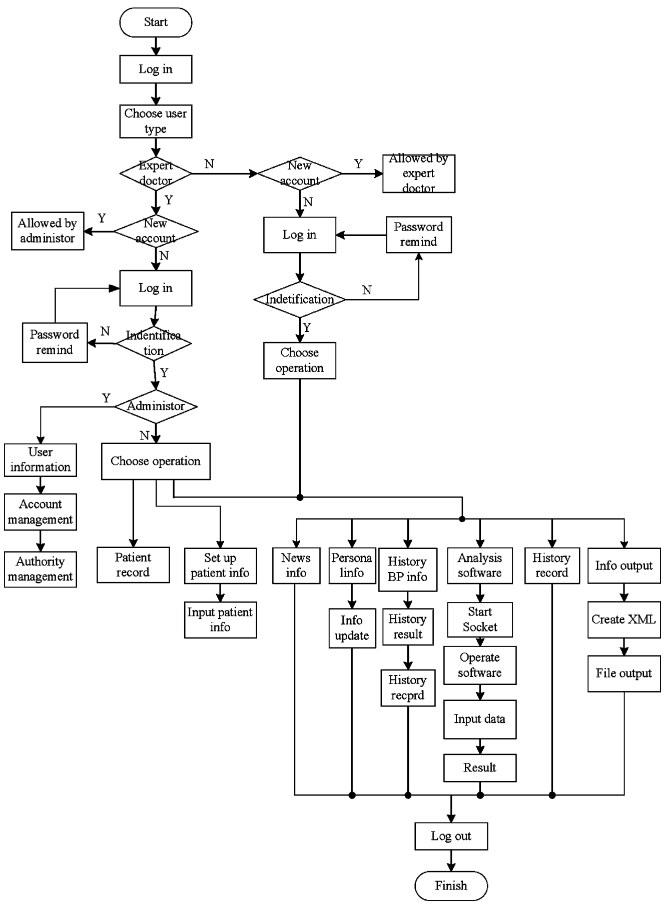


Fig. 9. Flowchart of Website management and analysis.

transmitted in real time through public phone networks; however, the voice quality still needs improvement.

C. Server Domain

The server domain of the "iCare-SHU" system is based on a service work station with Website service. The station is working like this: first, once the SMS receiver gets the message, the system will check whether this message is from an effective sender; if yes, then the useful information (user information/recording time/BP value) will be filtered from the message and the system will test the user information; if the user name is valid, other useful information will be stored into the existing database, which is a Structured Query Language (SQL) database.

A Website is developed in C# language. The flowchart is shown in Fig. 9. There are mainly two entrances: one for community doctors and another one for specialist. The patient's BP information is provided as Extensible Markup Language (XML) files, which are suitable for other commercial databases of hospital information systems in hospitals.

The database is composed of several kinds of information related to BP patients: basic information, such as ID number, medical insurance number, name, gender, birthday, address (mobile) telephone, etc.; community doctor information, such as ID number, name, department, etc. BP information, such as data, time, BP value etc. and alarm information, etc. This information can be accessed through the Web pages.

D. User Scenario

Next, we will present a usage scenario to demonstrate system functioning and usage.

"A hypertension patient goes to the CHC of his community and submits his mobile number. He need not submit any other information because the CHP has his electronic records, including his basic information. He pays half a year's service fees (which is 18 Euros), and then, gets a terminal of "iCare-SHU" system, measurement instruments, and a user mannual explaining how to use it, e.g., keep the same height with your wrist and heart when it is working.

The patient returns home and wears the sensor unit on his wrist. It looks like a watch (the aim of next-generation "iCare-SHU" measurement device); therefoe, he can work/do housework with it and it does not obstruct his activities.

The sensor is in "standby" mode until 8:00 A.M. The measurement times of 8:00 A.M., 12:00 A.M., 4:00 P.M., and 8:00 P.M. have been set before usage. When the patient gets up, the unit starts to measure his status, and then, the patient can measure his BP value with one button if it is working properly.

Five minutes later, his mobile phone receives a message from the CHP saying, for instance, "Dear Sir, your current BP level is too high. If you are not feeling well, please come to CHP for further diagnosis." This message reminds him that he has forgotten to take hypertension drugs the previous day. As a result, he takes drugs at once and he will not receive any more reminder messages that day.

The same scenario occurs several times overthe next few weeks, alarming the carer, who asks him to come in. At the CHP, all of his BP electrical information has been stored in the database and the doctor investigates some of the problems based on the information."

The advantage of this scenario is that the patient need not go to the CHC everyday, and it cuts down the time and costs. For some patients, it avoids BP measurement errors, well known to be related to psychological stress during a doctor's appointment. However, other scenarios are also possible and depend on local contexts.

III. System Materialization and Test

This session will introduce the validation of the recent concept of "iCare-SHU" systems and evaluation results of technical and user tests. These results will be used for system development in the next stage.

A. System Materialization

Since "iCare-SHU" is specially designed and developed for the local context and a main design criterion is low cost, the major innovation of the system is the simplified wearable device with affordable but reliable components and user-friendly interfaces for both patients and community doctors.

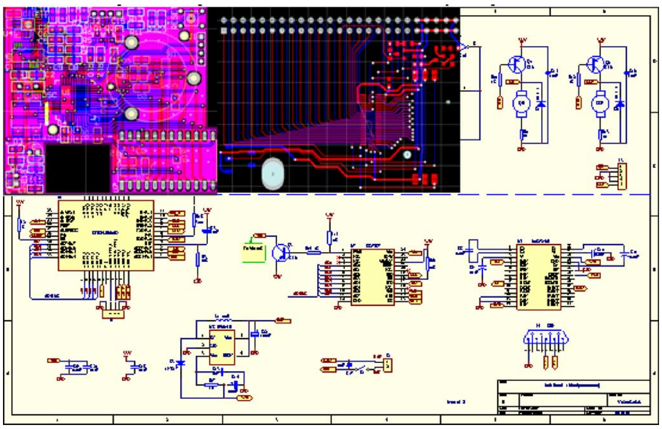
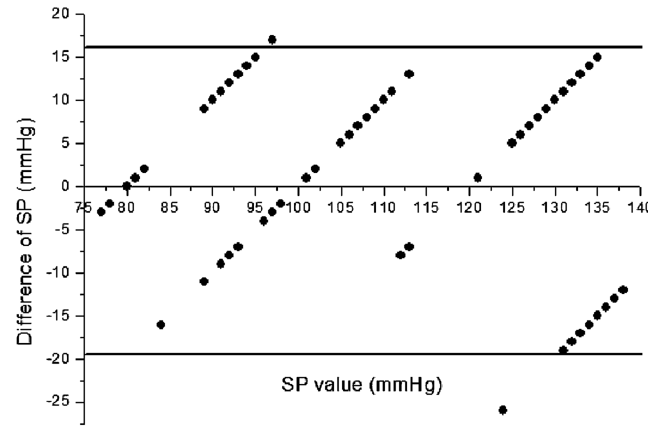


Fig. 10. Hardware of "iCare-SHU" wearable measurement device: PCB board.

Fig. 11. Simplified Chinese Website interfaces for community doctors.



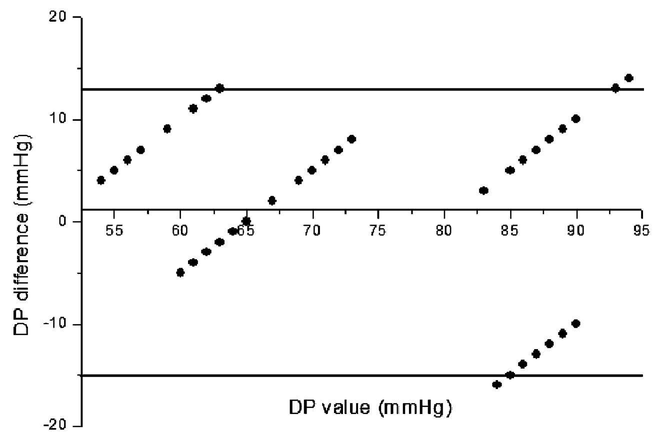


Fig. 12. (a) Difference of SP with our device and mercury manometer (unit in millimeter of mercury). (b) Difference of DP with our device and mercury manometer (unit in millimeter of mercury).

In the hardware part, only 55 components have been used to prototype the wearable device and the microchips are of low cost. Fig. 10 is the hardware board (printed circuit board (PCB) board) of the wearable device, which includes the different modules mentioned in the last section. The material of the product is plastic so that the device is handy and portable.

In the software part, a Website version based on C# has been designed, which is more acceptable to Chinese community doctors than the classic C version [22]. Fig. 11 shows examples of the Web pages. In our interface test experiments, all operations for one patient were finished within 2 min by community doctors, without any specific training on the system. (The basic computer skills such as "PinYin" input or mouse using are necessary.)

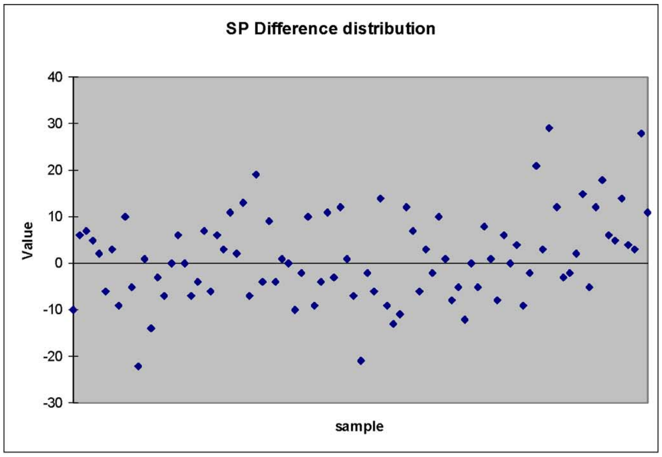
B. Device Test

To test the feasibility of development toward reliability and durability of our system, we set up experiments. Most of them focused on the wearable BP measurement device.

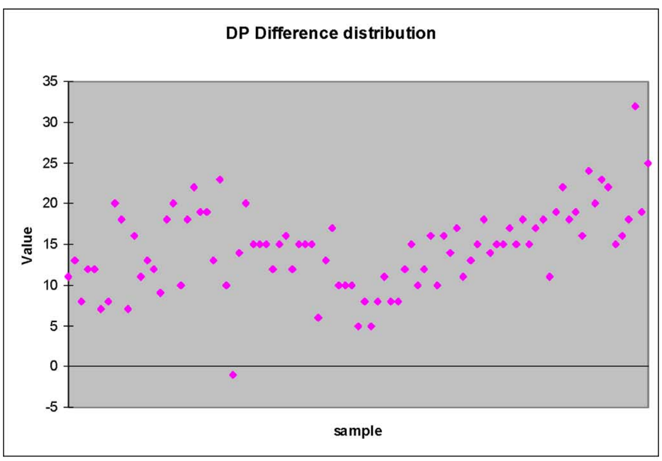
First, we developed an experiment system and chose four group standardized BP values (each 30 times): 80 mmHg/50 mmHg (SP/DP), 100 mmHg/65 mmHg, 120 mmHg/80 mmHg, and 150 mmHg/100 mmHg. The experiment platform includes five elements: 3-V digital power device (with the same two chargeable batteries), digital oscilloscope, mercury manometer, gas balloon pump, and the PCB board of the measurement device. Second, we input the standardized BP value as derived from a gas balloon pump controlled by a mercury manometer and measured the digital value of the measurement device by digital oscilloscope. Finally, we collected all data and analyze results, as shown in Fig. 12.

In Fig. 12, the 1imits of agreement for SP is -1.5 ± 10.8 mmHg and DP is 3.7 ± 5.9 mmHg. The maximan difference of SP and DP are $40/-19$ mmHg and $15/-18$ mmHg. This result shows that "iCare-SHU" measurement device is clinically acceptable according to BHS standard [23]; however, advanced optimizations are needed before transferring the prototype into a real product.

The reasons for the mistakes are complex, which may include electromagnetic interference, circuit mistake, and mechanical manufacture mistakes, etc. [24]. The next step will be to carry out some initial experiments for decreasing electromagnetic interference and circuit mistake.



(a)



(b)

Fig. 13. (a) User test SP difference between our prototype and Omron product (unit in millimeter of mercury). (b) User test DP difference between our prototype and Omron product (unit in millimeter of mercury).

C. User Test

Recently, the first-generation "iCare-SHU" system has also been implemented in Daning community, Shanghai as a pilot to reevaluate the concept. Ruijin hospital was chosen as the specialist hospital. In the user test, we invited 12 hypertension patients (three prototype wearable devices) into our experiments and two patients were tracked for more than one month. They were asked to use our measurement device and another existing BP wrist measurement product in the market (Omron HEM-1000). The two devices recorded BP values with a difference of several seconds. After the experiments, we collected and compared 90 points. The test differences are as shown in Fig. 13, and the result of Bland–Altman analysis for MP is as shown in Fig. 14. The average difference is 1.37 and 14.47 mmHg, while most of MP differences are distributed within 0–15 mmHg scale, according to Bland–Altman analysis.

Compared with the Omron product, DP value of our system is much higher, which might be due to BP measurement methodology (P5 algorithm) or engineering mistakes, such as electromagnetic interference, circuit mistake, and mechanical

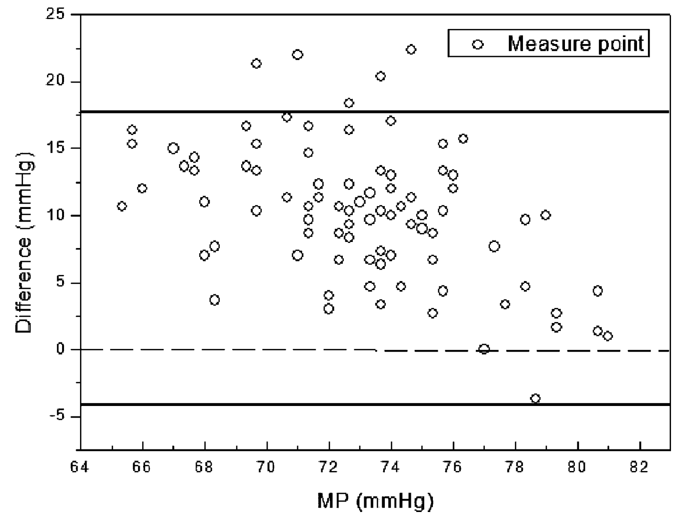


Fig. 14. Bland–Altman figure of MP based on 90 points.

manufacture mistakes. In next step, these factors will be considered to optimize our product.

IV. Discussion

Besides the user test on the wearable BP measurement device, other studies about whole system functionality, usability, and affordability were done through interviews and questionnaires. As a result, a few concerns still remain, which are as follows.

1) Technical optimization is still needed. There is a distance from current prototypes to commercial products. The optimization includes the accuracy of BP measurement (P5 algorithm), the reliability of the system (decrease device measurement mistakes and operation mistakes, like hand-to-heart height difference), and aesthetics improvement.
2) The proposed scenario about wearable device is another problem. From interviews with medical experts and industrial engineers who are working in healthcare companies and with users, we found that it is acceptable for patients to wear it all the day, but the device should be comfortable. The original type/size of the design is so big that it is not yet comfortable to wear all the time. Even if we would design a watch-size device, several questions remain. It should be validated that patients prepared to wear the watch-like BP sensor all the day? Will they become nervous when the unit is working? (The nervousness will result in a higher BP.)
3) The compatibility of the whole system should be considered. The system could be an open-looped system so that other sensors, such as ECG or blood sugar can be added into the system in the future. Also, this system is meant to be used as public medical education system to raise patients' awareness. Further studies about signal channel distribution and interference are also needed.
4) A sustainable business model such as involving governments is explored. Mobile phones (PDA and smart phones are not necessary) are very popular even in rural China, and they are only considered as SMS receiver in this system,

thus information and communication technology (ICT) is not very expensive here (2 Euro/month for SMS fee). Considering the trend in China of government constant ICT innovation for healthcare, we are conveniently exploring business models involving government. If this succeeds we expect the optimized product to economically acceptable for rural Chinese.

These and other questions will be investigated with the next generation of our system.

V. Results and Conclusion

To help in addressing the hypertension care problem, a wireless monitoring platform of BP by using SMS has been designed. Several aspects of the art of the technology are described in the design, such as automatic detection of patient's static status for measuring of pressure and intelligent data analysis: sign alarm and trend analysis (server domain). The investigations are meant to help to bridge the gaps in hypertension control, such as lack of continuous monitoring of patient and lack of hypertension records management, etc. Recently, this concept has been prototyped and revaluated. The conclusion is that the whole concept is feasible in China, and it can be developed toward sufficient reliability and affordability. Furthermore, the test result about wrist BP measurement device shows that the current device is feasible in order to transfer the prototype into a product after advanced optimization.

Also, we intend to develop the design further and carry out implementation. For this, a number of stakeholders are necessary. The design will function effectively when a complete design and development phase is executed, including attention to user testing and their needs, technological optimization, intensive involvement of the Chinese government, and a proper business model.

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