HUMAN-CENTERED PHONE OXIMETER INTERFACE DESIGN FOR THE OPERATING ROOM

Pulse Oximeter Interfaced to a Mobile Device for Anesthesia Monitoring in the Developing World

Walter Karlen, Guy Dumont

Electrical and Computer Engineering in Medicine (ECEM), The University of British Columbia, Vancouver, Canada

walterk, guyd @ece.ubc.ca

Chris Petersen, Jennifer Gow, Joanne Lim, Jules Sleiman, J. Mark Ansermino

Pediatric Anesthesia Research Team (PART), BC Children's Hospital, Vancouver, Canada

CPetersen, JGow, JLim, JSleiman @cw.bc.ca, anserminos@yahoo.ca

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Abstract: Mobile phones offer huge potential as platforms for clinical decision making in resource-poor and remote areas. We present methods for the development of a human-centered interface for anesthesia monitoring that is targeted to remote operating rooms in developing countries. The Phone Oximeter is compatible with major PC and mobile phone operating systems and is optimized for small phone screens. It displays vital physiological parameters in the corresponding clinical colours. Combined with an easily identifiable icon, this guarantees that accessibility is language-independent. To evaluate the acceptance and usability of the initial prototype of the Phone Oximeter, the Think Aloud process while completing a specific Task List, followed by the Mobile Phone Usability Questionnaire (MPUQ) were tested on 20 subjects with varying medical and mobile phone experience. The acceptance rate of 81.9 % from the MPUQ questionnaire clearly demonstrates the usability of the Phone Oximeter. The incorporation of the most relevant errors and complaints into the design of the next iteration of the Phone Oximeter prototype enhanced its capabilities further.

1 INTRODUCTION

Over two billion people do not have access to adequate surgical care (Funk et al., 2010). Operating rooms (OR) in developing countries often lack the expertise and essential equipment required to safely monitor patients during anesthesia and surgery (World Health Organisation, 2008). For example, continuous blood oxygen saturation (SpO_2) measurement is considered to be a minimum standard in the developed world but it is used in 50 % or less surgeries in many countries of the developing world (Funk et al., 2010). Limited access to such medical devices and the expertise needed to effectively use them constrains safe surgery.

We are taking a highly innovative and creative approach to address this issue by developing the Phone Oximeter[1] (Figure 1). Our novel software, which is hosted by a mobile phone connected to a pulse oximeter, creates a unique stand-alone medical device. At low cost, it is capable of monitoring SpO_2 and guiding anesthesia technicians in the safe management of their patients. Using established clinical guidelines, the software translates the clinical data it has extracted from the pulse oximeter into easily understood monitoring parameters and warning signals. Encoded expert advice will facilitate life saving decision support. The intuitive and human-centered display of symbols on the phone ensures that it is easy to use, regardless of literacy level or language. This monitoring will prevent clinical deterioration and save lives, as well as reducing device costs.

[1]http:///www.phoneoximeter.org

2 DESIGN REQUIREMENTS

Unlike currently used clinical pulse oximeters, because of its portability and battery-run operation, the inexpensive Phone Oximeter will be able to be used anywhere. Indeed, our innovative use of a mobile phone platform takes advantage of the already widespread distribution of these phones across the developing world. While pulse oximeters have been previously connected to mobile phones (Black et al.,

Figure 1: First prototype of the Phone Oximeter

2009; Moron et al., 2005), they have not been designed for use in the OR, do not meet current pulse oximeter design standards, nor do they include a goal oriented interface design. In addition, specific phone and language requirements limit the accessibility of these designs to the developing world.

We are harnessing the inherent computing power, peripheral resources (LCD display, audio, serial and USB connectivity) and energy storage of mobile phones to develop a medical monitoring device that can be easily deployed in the developing world at low cost. However, several engineering challenges must be overcome: 1) power consumption has to be minimized for maximal device efficiency and autonomy; 2) the user interface must be optimized for relatively small screen displays; and 3) the device must be optimized for use across a diverse range of hardware (e.g. peripheral connectors) and operating systems (OS) to ensure its portability between phone brands. In addition to these constraints, the successful design of the pulse oximeter interface for the OR must meet several design specifications: 1) adherence to standards for pulse oximetry (e.g. ISO 9919 - 05); 2) auditory and visual information and alerts to attract the attention of the clinician; 3) user friendly alert control and adjustment; 4) display of the raw photoplethysmographic (PPG) waveform to allow for the manual inspection of signal quality and feature interpretation; 5) signal quality indication; and 6) colour coding for the easy identification of vital signs. Additional requirements of this mobile phone application for the OR in developing countries are: 1) ease of use and navigation (usability); 2) low learning curve; 3) low risk for misinterpretation and error; and 4) provision of decision support. Specific capabilities of the mobile phone user interfaces and operating sequences will be integral to achieving these objectives. In this manuscript, we will focus on the human-centered interface design of the Phone Oximeter, and the evaluation and improvement thereof.

3 DEVICE DEVELOPMENT

3.1 Software

The software implementation is designed to allow the majority of development to be performed outside of the proprietary software development kit (SDK) frameworks. This maximizes portability across the most common mobile phone platforms currently available. The algorithms are implemented in C and the graphics rendering is performed in OpenGL, using only thin platform-specific wrappers to integrate with the underlying operating systems. The benefits of this are: 1) use of compiled C binaries will ensure that the algorithms maximally utilize the limiting processing power of the devices; 2) OpenGL hardware acceleration contained within the devices will greatly reduce the processing overhead associated with the graphical interface; and 3) ubiquity of C and OpenGL software elements in modern computing devices will make the prototype system easily portable to many other current and future platforms, and capable of leveraging a large body of existing and proven signal processing and interfacing algorithms.

The developed software application compiles to highly optimized ANSI-C. The application currently compiles on the principal OS like MAC OS X, Windows, Linux, and OpenBSD, and several of the most widely used mobile platforms including iOS, Android, and Maemo (Nokia) (Cozza et al., 2010). Ports to Symbian, currently the most widely used phone OS (Cozza et al., 2010), and Windows Mobile platforms are in progress.

The Phone Oximeter software is interoperable between 8 bit and 16 bit pulse oximeter devices from Nonin (Plymouth, USA) and automatically detects the correct protocol upon connection. It collects the PPG waveform and sensor alarms and stores them in a file on the device. This can be retrieved from the phone using a file transfer application for subsequent processing and display. The software is fault tolerant, and allows the pulse oximeter sensor to be inserted and removed on the fly.

3.2 Hardware

The hardware used in this study is an iPod Touch (Apple, Cuppertino, USA) hardwired via the serial port through the dock connector to a certified 8 bit OEM Nonin Xpod pulse oximeter sensor. Assuming that touch-screen technology will soon dominate the global market, we selected a more recent generation mobile device like the iPod Touch. Our iPod Touch is running iOS 3.1.3 and offers similar functionality as the iPhone, but at a lower cost. The large and bright LCD display makes it ideal for development in the OR. The Xpod pulse oximeter sensor provides the raw PPG waveform and processed trend values for SpO_2 and heart rate (HR).

The iPod connector provides a 3.3V UART connection that is directly compatible to the sensor pinout. The hardwire connection solution from the pulse oximeter to the iPod increases the connection reliability and powers the pulse oximeter sensor directly from the device. While a wireless solution (e.g Bluetooth) is also technically possible, it would be heavily dependent on interface and protocol, and would be supported by far fewer devices. For example, the iPhone Bluetooth stack is heavily restricted, and does not currently support the necessary Serial Port Profile (SPP). A challenge of our wired solution is to build adapters for varying connectors on the different phone systems.

3.3 Interface Evaluation

The user interface design process was started by assembling 20 cardboard prototypes with differing printed oximeter interface concepts and the same physical dimensions as the actual iPod Touch device. Through a participatory design process that included discussions with stakeholders, these cardboard mockups served to define the initial layout of the first software prototype of the Phone Oximeter.

Following institutional ethics approval and informed consent, 20 subjects (Table 1) working in a hospital environment were recruited for a usability study of the Phone Oximeter for anesthesia to identify design flaws and opportunities for design improvements. Demographic information, including experience with the iPod (or any other iOS device) and pulse oximetry, was collected (Table 1). Familiarity with mobile phone use was evaluated by asking subjects to choose a label from the IDC mobile phone user label (Table 2, International Data Corporation, 2003). Users were given a 23-item Task List (Table 3) to complete with the Phone Oximeter and were not given any training or instruction. An audio recording was taken during the evaluation and subjects were asked to Think Aloud (Someren et al., 1994). The experiment was conducted in a quiet room with a moderator and observer. The errors (tasks that required more than one attempt and/or requests for assistance) and time taken for each task were recorded. Four de-briefing questions and a 55-item modified Mobile Phone Usability Questionnaire (MPUQ, Ryu and Smith-Jackson, 2006) was administered following the completion of the Task List. The MPUQ was analyzed using categorical response data (5 = Strongly Agree to 1 = Strongly Disagree). The categorical variables were reversed (i.e. most desirable response was 1 rather than 5) for three questions. For these reversed questions, the response was subtracted from 5 to allow for summary analysis.

Table 1: Demographics of the study subjects. Medical Doctor (MD), Registered Nurse (RN), Anesthesia Assistant (AA), Anesthesia Resident (R), Medical student (MDS)

	MD	RN	AA	R	MDS
Nb.	10	5	2	2	1
Age (mean)	45.2	46	41	33	27
Age (SD)	9.0	12.6	5.7	5.7	0.0

Table 2: Subject responses to the IDC mobile phone user metric (International Data Corporation, 2003): Display Maven (DM), Mobile Elite (ME), Minimalist (M), Voice and Text Fanatic (FA)

IDC Label	DM	ME	M	FA	DM+ ME+ FA	M+ FA	ME+ FA
Nb.	1	0	11	1	1	4	2

4 RESULTS

4.1 Interface Evaluation

All subjects had previously used a pulse oximeter but nine had never used an iPod Touch. All subjects required more than one attempt to complete at least some of the tasks. Ten of the 23 tasks required more than one attempt by at least one subject (Table 3). A failed attempt was deemed to be any erroneous touch, menu selection, navigation, or identification. The number of errors observed between subjects with or without iPod Touch experience was similar (3 ± 0.5 vs 3.4 ± 1.8 respectively, per subject). The task that most commonly required more than one attempt was “Task 10: Changing the weight of the patient”. All but one subject needed more than one attempt to complete this task (Table 3). This was the first time that subjects encountered the Settings screen, as well as the first experience with the spinning wheel. Table 3 shows how subjects improved after completion of this task by having lower completion times for the

Table 3: 23-item Task List and results of the study subjects. The second column presents the number of subjects that were not able to complete the task on the first attempt or required assistance. The third column presents the mean ± SD completion time for each task

	Task	Users with >1 try	Completion Time mean ± SD [s]
1	Place sensor on finger	0	–
2	Start Phone Oximeter from iPod menu screen	0	14.0±7.0
3	Identify what value is alarming	2	5.5±4.4
4	Silence alarm generated	0	4.6±4.9
5	View alarm details	2	4.9±5.4
6	Identify the cause of the alarm	1	9.5±11.3
7	Change patient mode from neonate to adult	7	17.3±15.6
8	Back to Home screen	0	–
9	Identify the weight of the patient from the Home screen	0	1.7±0.9
10	Change weight from 70 kg to 111 kg	19	41.6±25.5
11	Back to Home screen	0	–
12	Identify the heart rate UPPER Limit	0	6.1±8.1
13	Change heart rate UPPER limit to 128 beats/min	3	18.5±11.8
14	Back to Home screen	0	–
15	Identify the relative signal quality for heart rate	4	17.5±13.7
16	Change trend line length to 3 min	6	27.5±19.8
17	Back to Home screen	0	–
18	Identify O2 saturation LOWER limit	0	4.3±7.4
19	Change O2 saturation LOWER limit to 85%	2	9.5±4.7
20	Restore the default values for adult	9	17.4±15.3
21	Change patient mode to child	0	3.8±3.4
22	Back to Home screen	0	–
23	Shut down Phone Oximeter	0	–

following tasks. The mean time to complete the entire Task List was 203.39 ± 56.4 s. The task of changing an alarm limit took longer than the other tasks (Table 3). The MPUQ analysis showed a high degree of overall satisfaction with the use of the Phone Oximeter (Table 4). Design improvements for the second prototype of the Phone Oximeter interface were based on the most frequent user errors (Table 5).

4.2 Second Design

Based on the subjects' comments during the Think Aloud process and the errors committed during the experiments, we identified the most important and frequent complaints regarding the Phone Oximeter (Table 5). Based on these common errors, we modified the interface to better satisfy the users' needs and to render the system more intuitive. The second Phone Oximeter interface prototype consists of four main tabs (Figure 2):

1) The Home screen displays the vital parameters of HR, SpO_2 and respiratory rate (RR) in the corresponding clinical colours and easily identifiable icons. The raw PPG waveform is displayed in combination with the SpO_2 parameter. A signal quality index (SQI) represented by coloured bars and a trend graph is displayed for each vital parameter. Within the trend graph, the current alarm threshold settings are displayed as horizontal lines. On the top bar, the patient demographics (age group and weight), and battery capacity are displayed. The bottom bar contains the tabs to navigate between the screens.

2) Three buttons in the top bar of the Settings screen allow switching between age groups (neonate, pediatric, adult) and reset to the default settings. Spinning wheels are used to input patient weight, upper and lower alarm thresholds for each vital parameter, and the window length for the trend graph.

3) The Messages screen displays the current time on top. Messages are displayed in the main window using red, orange and yellow colour codes to denote importance (high, medium, low, respectively).

4) The fourth tab (as shown by an illumination icon) allows the Phone Oximeter to enter a power save mode and disables the LCD screen. The auditory functions remain enabled which allows for low-power operation without disrupting information transfer to the user.

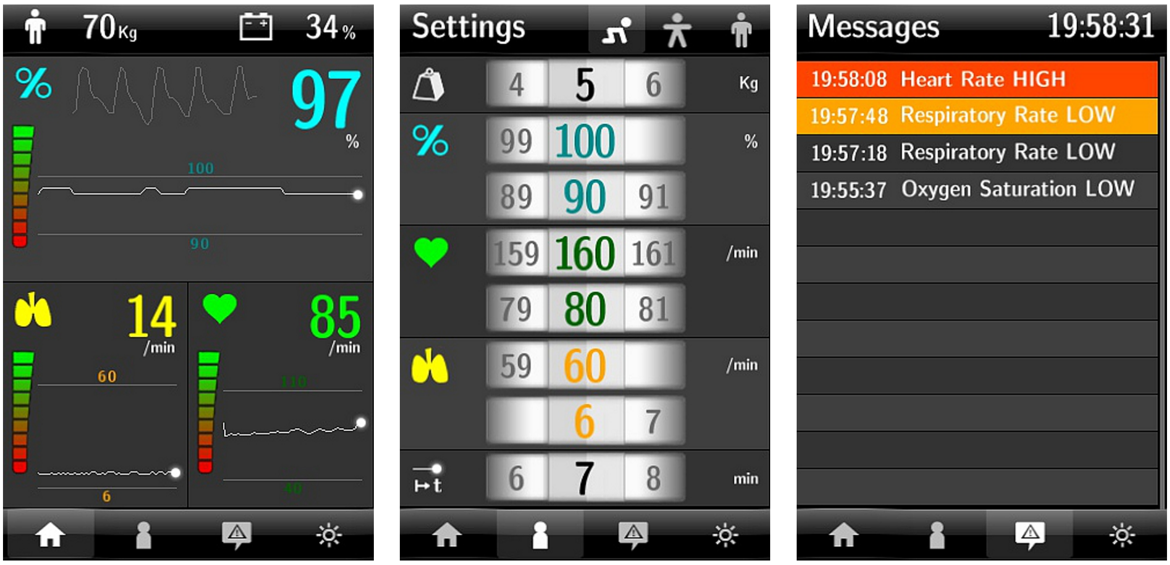
The Phone Oximeter software includes an auditory interface consisting of a sounded heart rate with SpO_2 modulated pitch in accordance with clinical standards, and three priority levels of auditory alarms following accepted standards for commercial physiological monitors.

Table 4: MPUQ analysis levels

Factor	Nb. of questions	Perfect score	Total score	Satisfaction [%]
Ease of Learning and Use (LEU)	21	2100	1747	83.19
Helpfulness and Problem Solving Capabilities	3	300	243	81.00
Affective and Aspect	2	200	185	92.50
Multimedia Properties (AAMP)	9	900	712	79.11
Commands and Minmal Memory Load (CMML)	6	600	480	80.00
Control and Efficiency (CE)	8	800	668	83.50
Typical Tasks for Mobile Phone	1	100	85	85.00
Typical Tasks for Phone Oximeter	5	500	386	77.20
Total	**55**	**5500**	**4506**	**81.93**

Table 5: Design improvements for the second Phone Oximeter prototype

Error / complaint	Nb. of subjects with error / complaint	Improvement
Users were unclear which parameter was alarming from the Home screen	10	Brighter, flashing alarm state
Users tried to press the top bar in order to access Settings screen	19	Touch functionality added to top bar of the Home screen
Users were unclear which icon represented the trend line	14	New icon for trend line in Settings screen
Users were unclear what the original SQI symbols meant	11	Redesign of SQI to more closely resemble industry standards
Users felt that the alarm limits were faint and unclear.	7	Colour-coded alarm limits on Home screen



(a) Home screen (b) Settings screen (c) Messages screen

Figure 2: Revised Phone Oximeter interface featuring four screens (Home, Settings, Messages, and Powersave (not shown))

5 DISCUSSION AND CONCLUSION

The Phone Oximeter for anesthesia provides a low cost solution for monitoring pulse oximetry in ORs around the world. It provides all of the important features required to provide safer patient monitoring through pulse oximetry. The major engineering challenge was to provide a human-centered, user-friendly and language independent interface that is deployable on a multitude of platforms and OS. This was addressed using OpenGL that can be embedded with an OS-dependent hook into the native code. The interface design was improved based on usability studies using a task list and a modified MPUQ. Whereas the study participants had a diverse range of experience and demographics that was helpful for interface design improvement, we could not test the effect of language or cultural barriers, as all subjects were English speaking and living in Canada. We are currently conducting the same usability studies in Africa with a wide range of potential end users (e.g. anesthesia technician). The high acceptance rate obtained from our Canadian study and the intentional minimal use of English words in the Home and Settings screen suggests that adoption could be universal.

The Phone Oximeter application prototype consists of our developed software and interface, an iPod Touch and a Nonin Xpod pulse oximeter. The iPod Touch was able to provide power for the pulse oximeter sensor for five hours, which included continuous recording and display of data without dimming the screen. Most phones have a substantially larger battery and will, therefore, be able to operate the application for a longer period of time. This will be sufficient for most operating scenarios conducted in the developing world. If required, additional autonomy could be provided by an additional battery pack to power the pulse oximeter sensor independently.

The current prototype is based on a wired connection between sensor and phone. This is an advantage for power consumption and designing the communication protocol, since less complex layers are required. However, our current implementation does not provide the required electrical isolation between the iPod Touch and oximeter device. This will be solved in upcoming versions with an improved electronic isolation circuit or through wireless communication between sensor and display device. This will, however, increase power consumption and costs, and reduce autonomy.

Further work will include the improvement of the embedded algorithms for the computation of HR, RR and SQI. We also plan to include a clinical decision support engine that will have the potential to increase the reliability of the warning and alarm messages.

We have demonstrated an approach to design a user interface for visualization of HR, RR, and SpO_2 data for use on a size-restricted mobile phone display to be used in remote locations by healthcare workers with little to no prior training. This will offer great potential in deploying low-cost, life-saving devices in the ORs of developing countries without significant investments in training and infrastructure.

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