Vibro-Monitor: A Vibrotactile display for Physiological Data Monitoring

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ABSTRACT
Vibro-Monitor is a new wearable vibrotactile display used to present physiological data to an anesthesiologist during a medical operation. In the current physiological data monitoring system, visual and sound cues are used to display a patient's information to clinicians. However, such system distracts clinicians from monitoring patients and cannot be used in an operating room environment that is constantly polluted by other noises.

In this paper, we present the implementation of an innovative tactile display, the designs of an alarm scheme and a continuous feedback scheme. The tactile display's and the vibration patterns' designs are based on researches related to human perception and psychophysics. We also evaluate the Vibro-Monitor using both pseudo data and real clinical data. Possible improvement over the device is also discussed.

Keywords
Vibrotactile, tactile, wearable, vibrating motor.

1 INTRODUCTION

Vibro-Monitor is a device attached to an anesthesiologist and presents physiological data to he/she using vibration. In an operation room (OR) environment, a patient's physiological status like heart rate (HR), blood pressure (BP), electrocardiogram (ECG) and entropy of brain activity etc, are of great interest. A visual display is traditionally used to monitor these data. However, the visual display makes it impossible for the anesthesiologists to monitor the display and continuously observe the patient at the same time. To solve this problem, primitive single parameter tracking audio alarm is introduced. The primitive alarm solves the problems with monitoring, but at the same time introduces the unpleasant noises into the OR. Moreover, false alarms are frequently generated by artifacts. Efforts have been put into the implementation of a new multi-parameters alarm system that eliminates the problem with the false alarm, yet leaving the noise problem unsolved. The existing problems of the current monitoring and display system are as the following:

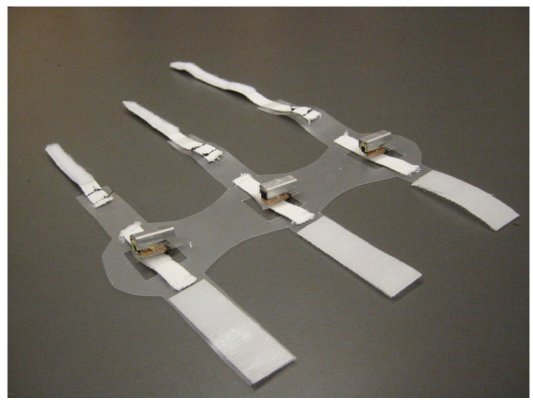

Figure 1 The Vibro-Monitor. It consists of three vibrating motors and is worn on a user's inside forearm. (NB: the hardware interface is not shown in the diagram.)

- It is impossible to monitor the display and the patient at the same time using the visual display.
- With the single parameter audio alarm, there are many false alarms, which renders the alarm useless.
- With the multi-parameter audio alarm, the false alarm issue is well addressed. The OR environment, yet, is already polluted by noise before the introduction of audio alarm. Hence, auditory alarm is not the ideal solution to the problem.

The above issues motivate us to explore another way to display information.

Skin is the largest human sensory organ and forms roughly a surface area of $1.8m^2$ of mechanoreceptors that is responsible for the sense of touch [1]. Moreover, the sense of touch is five times faster than the sense of sight [15], and human takes about 5ms to sense two consecutive tactile point stimuli [1]. Therefore, a tactile display is able to provide clinical data to anesthesiologists during an operation.

Based on the evaluation of the current monitor system and the observation on the routine work of an anesthesiologist, the tactile display should be wearable, light in weight and unobtrusive to everyday work. Also, the device should have low power consumption. Finally, the information transmission rate should be high enough to allow real-time information feedback such that the anesthesiologist may respond to abnormal situations immediately.

Our wearable monitor, called Vibro-Monitor (as shown in figure 1,) uses light-weighted vibrating motors to deliver information. It is placed on an anesthesiologist's forearm

Since this is the first prototype, we aim to develop a wearable physiological data monitor that is capable to deliver HR status information using a minimum number of tactors. HR parameter is chosen because it is always the most important parameter in the operation room.

Section 2 of this paper first discusses current research on wearable devices and tactile displays, and the reason vibration is chosen to provide tactile sensation. Then, the choice and placement of tactors will be discussed based on research on perception and psychophysics. Section 3 discusses the design of our physical devices and the simulation scheme. Section 4 describes the user tests and evaluation of results. Lastly, section 5 discusses the possibility of future development.

2 BACKGROUND RESEARCH & DESIGN PARAMETERS

This section discusses previous work on wearable tactile display, methods of providing tactile sensation, and human perception. The design of the Vibro-Monitor is based on analysis of previous work that is discussed in this section.

2.1 Wearable Tactile Display

The use of wearable device implies the use of the human body as a support environment for the product [6]. Currently, research is performed to integrate a tactile display to the human body. For example, a vibro-tactile feedback glove called CyberTouch™[8], a shoulder pad insert vibrotactile display [17], a tactile vest [5], and the *Sprout* conceptual earpiece tactile display [5]. These devices aim at providing a wearable tactile display that is light, silent, tiny, low in operating power, and has the ability to deliver tactual sensation. The placement of the tactile display is also an issue. Although fingertips and palms have the finest spatial resolution, a placement of device over these locations affects activities of daily living. [5] suggests that the collar area, back of the upper arm, forearm, chest, waist and hips, thigh, shin, and the foot (dorsal) are the most unobtrusive areas. Also, they have a large surface area for sensation.

In this application, the inside of the forearm was chosen to place the Vibro-Monitor. The inside of the forearm has a relatively low degree of movement and is unobtrusive. Moreover, it has the highest spatial resolution among the unobtrusive areas mentioned before [3].

2.2 Method of Tactile Sensation

There are various methods to generate skin sensations and they can be divided into five categories: piezoelectric actuators, electrical pulses, thermal feedback, voicecoils, and motors.

Piezoelectric actuators deforms by a few micrometers to 1-2 millimeter when a voltage is applied. Piezoelectric bimorph is commonly used as an actuator to drive tactile matrix [19]. However, a large operating voltage is required (around 60V to 300V) to bend the bimorph by 1-2mm. Not until recently, Poupyrev et al have developed the TouchEngine™ piezoelectric actuator that is capable of bending 0.28um at 8 to 10V[15]. However, the fabrication of the actuator is complex and expensive.

Electrocutaneous display uses anodic and cathodic current to selectively stimulate each type of mechanoreceptors [10]. In [9], Kajimoto et al have developed an electrocutaneous display called SmartTouch to translate visual surface information to electrical pulses. Although electro-tactile display is light and have no moving parts, it may cause discomfort and pain to the user.

Thermal tactile devices usually are based on Peltier elements. Peltier elements generate rapid heating and cooling in the order of 20°C /sec over a temperature range of -5 to 50°C [15]. However, thermal tactile display is not suitable for transmitting information because it generally has slow response, poor localization, prodigious capacity for adaptation and summation [11].

Solenoids like voicecoils are used to generate vibration, e.g. Active Click. However, sufficient vibration amplitude can only be produced at the resonant frequency [4]. Therefore, complex vibration patterns cannot be represented.

A vibrating motor uses a counter-weight and a motor to generate vibration. Compared with piezoelectric material, they provide larger amplitude of vibration at a lower cost and smaller size. Also, motors can be operated at a low voltage (1V to 12V). Toney at al [17] have implemented a shoulder pad insert vibrotactile display using pancake motors and mobile phones have vibrating motors to signal users when phone calls arrive.

Based on the above analysis, the vibrating motor is most suitable to our application because they have a low operation voltage and are small in size. Most of the vibrating motors vibrate at a frequency around 100Hz to 200Hz. This range of frequency is suitable to stimulate Pacinian mechanoreceptor whose threshold frequency is around 200Hz [12]. The details of the choice of motor will be discussed in section 4.

2.3 Perception and Psychophysics

The Vibrotactile spatial resolution on skin is very important as it determines if a human can sense the vibration patterns and interpret the information. According to Cholewiak et al [2], there are a number of stimulus parameters that we should consider when determining where to place the vibro-tactors. These parameters are: the location, spatial separation distance between vibro-tactors, and frequency of tactors. Besides adaptation to vibrational stimuli, temporal and spatial issues also need to be considered when designing the vibration patterns.

2.3.1 Location of Vibro-tactors

The law of mobility from Vierordt states that the closer the location to an anatomical landmark (e.g. joints like wrist or elbow), the better the absolute localization of the stimuli. Therefore, human localizes the same vibration better at a body position where movement is allowed. Cholewiak et al also did vibrotactile experiments to show that the percentages of localization were between 72-82% at the elbow and wrist, and 45% at the middle of the arm when tactors are placed at 25mm apart. The subjects are students aged from 18 to 30 years old [2]. Also, they show that accuracy of localization at less sensitive locations can be improved if a higher frequency vibration than that at the more sensitive locations is used.

2.3.2 Separation of Vibro-tactors

The forearm has a two-point threshold of 38.5mm based on [e]. In [2], Cholewiak's experiments proved that the increase of vibrator separating from 25mm to 50mm increased the recognition accuracy from 46% to 66%. It is reasonable to assume that the suitable separation of vibrotactors should be greater than 50mm in our Vibro-Monitor. A larger separation can overcome mechanical and physiological interactions that would interfere the vibrotactile location.

2.3.3 Frequency of Vibro-tactors

Cholewiak et al [2] showed that there is minimal effect in varying frequencies between 100Hz to 250Hz on vibrotactile stimulation. They also pointed out that a number of cutaneous systems like Tan's multifinger tactual display [16] did not increase the information transmission rate by changing the stimuli frequency, intensity and location.

2.3.4 Adaptation to Vibration Stimuli

Sensory adaptation happens when the stimulation signal is physiologically adapted by the user's sensation system and becomes unnoticeable to the user. Hahn's experiment in 1966 and 1968 shows that when an onset of vibrotactile stimuli continuously applied to the user's finger (10 to 1500 sec), the threshold level of the intensity increases [18]. It means that, the longer the time the same stimuli is applied to the skin, the more likely the user will adapt to the stimuli and may eventually ignore it.

2.3.5 Temporal and Spatial Issues

If the information is presented in a way based on the relative changes of stimuli or time-continuous wave patterns stimulating the skin, the relative position of the vibro-tactors is more important than that of the localization. If the information is presented by a coding scheme, the accuracy of vibration senses will depend on the absolute localization of activity in an array [2]. Consequently, our representation schemes will be using both wave and spatial patterns to convey information instead of coding.

Tan et al found out that when digits were simultaneously stimulated on multiple fingers with the same waveform, the subjects were unable to distinguish two-digit signals from three-digit signals. Finally, when multiple digits were stimulated with different waveforms of the same duration, the subjects could not reliably associate a waveform with a digit correctly [16]. Although our display is to be worn on the forearm, not the finger, it still uses the same sensory system. Hence, we avoid stimulating two or more locations at any given time in our representation schemes.

3 DESIGN AND IMPLEMENTATION

In this section, the design and the implementation of the Vibro-Monitor are discussed based on the above design factors. We discuss about the choice of motors, the hardware design and the stimulus scheme.

3.1 Choice of Motors

Vibrating motors are chosen because they operate at low voltage and are light-weighted. Digital signal can be easily used to control motor so that it will be easy to integrate with wireless communication technology. The two types of vibrating motors that are available in the market are considered: the cylindrical type and the pancake type. Cylindrical vibrating motors are preferred over pancake motors for two reasons:

- Available cylindrical vibrating motors rotate at a speed ranging from 7000 rpm (116.7Hz) to 11000 rpm (183Hz) [13] while pancake motors rotate at 4500 rpm (75Hz) [14]. Therefore, vibrating motors vibrate at a frequency closer to the threshold of Pacinian mechanoreceptors.
- Both motors provide circular vibrations. However, due

to the physical dimensions of the motors, cylindrical motors are more suitable in generating vibration perpendicular to a surface (longitude waves). The pancake motors are suitable for generating vibration parallel to a surface (shear waves). Since shear waves spread the vibration over a large area and increases the surface area of skin that senses the vibration, cylindrical motors are chosen. Based on our preliminary testing on the motor, we find that the localization of the vibrating motor is better than that of the pancake motor.

Panasonic's KHN4NB vibrating motors are chosen as the tactors. These motors vibrate at 9700rpm (162Hz) and provide a force of 0.68N without load. They operate at a low voltage (1.1 to 1.7V) at 125mA. Also, they are light (0.59g.)

3.2 Hardware Implementation

The Vibro-Monitor consists of 3 vibrating motors, 3 current amplifiers, and an interface board. A commercially available interface board, the PhidgetInterfaceKit 8/8/8, is used to control the motors from the computer [7]. The board has 8 digital outputs, three of which are connected to three current amplifiers. Three vibrating motors are then connected to the current amplifiers. These 3 motors are then connected to the user's forearm at locations depicted in figure 2.

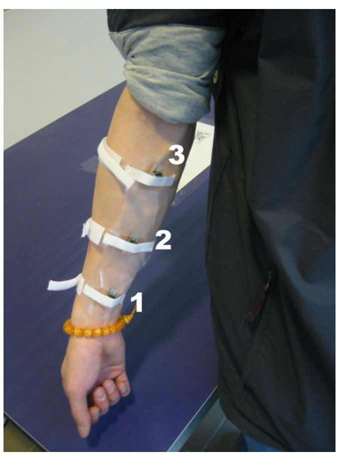

Figure 2 The location of the vibro-tactors on the inside of forearm.

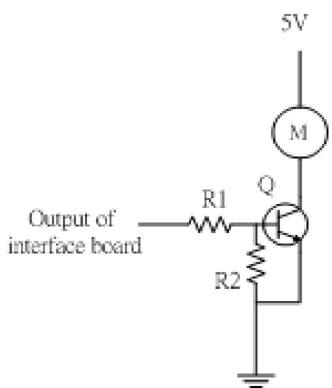

Figure 3 Circuit diagram of the current amplifier.

3.2.1 *The Current Amplifier*

Since t, the current amplifiers (as shown in figure 3) are kept as simple as possible. Each amplifier consists of 2 resistors and a 2N4124 NPN bipolar junction transistor. For motors 1, 2, and 3, R1 has the value of 4.7 kΩ, 2.4 kΩ, and 4.7 kΩ respectively, while R2 is 4.7kΩ in all three amplifiers. A smaller value of R2 gives motor 2 more current compared to motor 1 and 3 upon onset. Such selection is made because motor 2's location is less sensitive to vibration [2].

3.2.2 *Mounting and Contactor*

The KHN4NB motors are numbered 1, 2, and 3, and are mounted on the wrist, mid forearm, and the inner elbow respectively. The motors are mounted on the arm with elastic strips. The separation between the motors is 6cm. As shown in figure 1, the metallic contactors separate the motors from the skin preventing the users' skin from interfering with the motors' rotations. The metallic contactors are made of aluminum and have a base area of 1.6 cm^2. The separation and the base area are selected based on the discussion given in section 2.3.2 and the work of Cholewiak et al [2]. Also, each motor is mounted using an elastic band to help the localization of the vibration.

3.2 Stimulus Scheme

The stimulus scheme refers to the way Vibro-Monitor communicates with the user. Since this is the first prototype, only the HR is communicated to the user by varying the vibration length, idle time, and the stimulation location.

In this section, we present two possible stimulus schemes to represent the changes in HR. The Vibro-alarm scheme encodes different levels of changes into six possible patterns; while the vibro-feedback scheme presents changes in HR by modulating the HR value to pulse per minute, so that the user can interpret the level of changes in terms of relative temporal separation between vibration pulses.

3.2.1 *Burst Period and Minimum Idle Time*

Since digital output ports are used to control the motors, square wave is used for stimulation. The time between the on and the off state of a motor is referred to as the burst time (T_s) or burst period, and the time between two consecutive bursts is referred to as the idle time (T_i).

Based on preliminary testing on ourselves, it is found that T_s=200ms with a minimum T_i of 100ms give the best sensation and the gap between burst is the easiest to distinguish. Note that the T_s+minimum(T_i) is equal to 300 ms, giving a theoretical maximum information transmission rate of 10 bits/seconds (3 motors * 1 bit / motor / 300 ms).

3.2.2 *Alarm Scheme (Vibro-Alarm)*

For the reasons mentioned in section 2.3.5, the vibro-alarm stimuli used in this scheme utilize both spatial encoding and waveform patterns to convey information. There are six types of alarms in total, which can be classified into two categories: increasing and decreasing. Each category has three levels corresponding to a 10%, 20%, and 30% change in HR over the last 5 seconds. The timing diagrams of the alarms' stimulus are given in figure 4. When an alarm threshold has been satisfied, the alarm will be displayed to the user using a long burst (900ms) followed by a sequence of short bursts (200ms). The type of alarm is indicated by the location of the first burst: motor 1 for an increasing alarm and motor 3 for a decreasing alarm. After the first burst and an idle time depending on the type of alarm, one burst (for level 1 and 3) or two bursts separated by 100ms (for level 2) will be sent to motor 2. After another T_i, the last burst will be sent to motor 3 or 1 depending on if the alarm is of increasing or decreasing type. The idle time, T_i, is 500ms, 300ms, and 100ms for level 1 (10%), 2 (20%), and 3 (30%) alarms respectively. Finally, this pattern will be repeated three times for level 1 and 2 alarms, and four times for level 3 alarms.

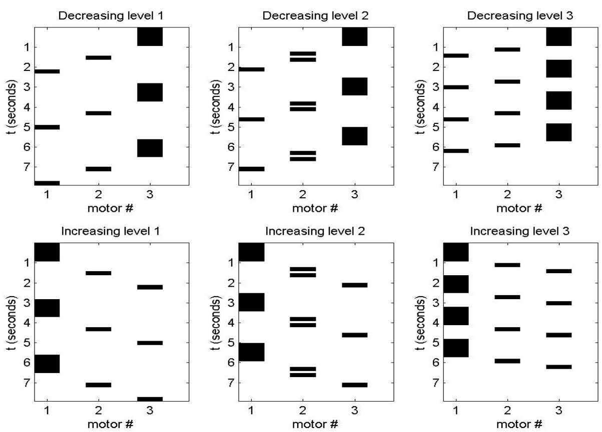

Figure 4 The Timing Diagrams of the Six Vibro-Alarms Stimuli Patterns.

3.2.3 Continuous Feedback Scheme (Vibro-Feedback)

In the continuous feedback scheme, the HR of the patient is continuously displayed by sending short (200ms) bursts to the user. The bursts will be sent to motor 1, 2, and 3 recursively, separated by an idle time on the current value of HR. For example, if the current HR is 60 beats / minutes (bpm), there will be 60 bursts / minute. If the HR is 120 bpm, there will be 120 bursts / minute. To the user, it will feel like a wave pattern whose speed changes with the current HR.

4 USER STUDY AND DISCUSSION

The goal of user testing is to investigate the usability of the vibration pattern in terms of:

- **Learnability and Memorabilty** – can users learn and remember different alarm patterns and distinguish the different rate of vibration in the continuous feedback situation?
- **Comfortability and Satisfactory** – do users feel comfortable using the Vibro-Monitor?
- **Adaptation** – do users adapt to the vibration? Can they recognize different vibration patterns?
- **Resolution** – how well can users distinguish different rates of vibration in the continuous feedback case?

The efficiency and productivity of the vibro-alarm were investigated by comparing it to the auditory alarm method. Lastly, in order to investigate if the vibro-patterns can be applied to monitor physiological data, a set of clinical data was used and tested on an anesthesiologist. Subjects were also required to fill in questionnaires.

The testing is divided into 2 phases: Usability Testing using Pseudo-data and Usability Testing using Real Clinical Data.

4.1 Phase I: Usability Study using Pseudo-data

This study aims to test the usability of the vibro-alarm scheme and vibro-continuous feedback scheme. Also, the vibro-alarm will be compared to the auditory alarm so to investigate the efficiency of the vibrotactile alarm. Five subjects with no anesthetic background are invited to participate in the test. This phase consists of three tests.

4.1.1 Vibro-Alarm Test

This test aimed to investigate how well a subject could recognize vibrotactile alarm patterns. At the beginning of the test, the subject was trained to memorize the 6 vibro-alarm patterns. The subject was allowed to feel the patterns for as many times as he/she wanted. The number of times the subject replayed the pattern was noted. Once the subject felt confident, he/she could start the training test.

The training test aimed to determine how well the subject memorized alarm patterns. Each trial consisted of 12 randomly generated patterns. The subject would then try to recognize the pattern and the accuracy was recorded. The training would be stopped when the subject achieves 80% accuracy within a trial.

After the training test, the subject was asked to try a 30 minutes alarm test with distraction. In the 30 minutes, 80 alarm patterns were generated irregularly (in different time intervals) while the subject was listening to music. He/she could also search the Internet and chat with us. Whenever the subject noticed an alarm, he/she would input the alarm pattern that he/she recognized and recorded it in our log. If he/she noticed an alarm but could not determine the alarm type, he/she would input “cannot recognize alarm”. The result of how the subject recognized the alarm is recorded.

4.1.2 Auditory Alarm Test

This test aimed to test how well a subject could recognize auditory alarm patterns. The testing procedure was the same as the vibrotactile alarm, except that the vibrotactile alarm patterns are replaced by sound patterns. The auditory patterns closely followed the alarm sound of the present physiological monitor.

4.1.3 Vibro-Feedback Test

This test aimed to test how well a subject could recognize vibrotactile continuous feedback patterns. At the beginning of the test, a subject was asked to feel the vibration rates at different HR rates. For example, at HR = 60bpm, the inter-vibration interval was around 1 second. The HR was varied by adjusting the slider of the GUI. When the subject felt confident, he/she could start a 30-minute test with distraction.

In the 30-minute test, the heart rate was continuously fed to the subject as vibrations. The subject was required to listen to music as a distraction. He/she could also search the Internet and chat with us at the same time. Whenever the subject noticed a change of HR, he/she would change the slider to indicate the HR he/she was feeling. The result of how the subject changing the slider value was recorded throughout the test.

4.2 Phase II: Usability Study using Clinical Data

Phase II's study aimed to test the usability of the vibro-alarm and vibro-continuous feedback scheme on an anesthesiologist. An anesthesiologist was invited to participate in the test. This test was similar to the Usability test using pseudo-data, except that the pseudo-data was replaced by real world clinical data and the auditory alarm testing is removed.

4.3 Results

After the phase I and II user studies were finished, the results were analyzed and tabulated. This section presents the analysis along with supporting tables and plots.

4.3.1 Analysis of Phase I Results – Pseudo-data

Based on the testing results and post-testing survey, it is noticed that the vibro-alarm patterns were easily distinguished. The subjects expressed that it was not difficult to distinguish between the different alarm patterns. The number of times a subject had to feel each type of alarm before he/she could remember all the alarm patterns is given in table 1. On average, the subjects took 14 times to learn vibro-alarm patterns compared to 11.2 times for audio-alarm. From the training, it was noticed that increasing level 3 vibro-alarm was the most difficult to memorize (repeated 3.0 times in average) while decreasing level 1 was the easiest to memorize (1.8 times). Other vibro-alarm patterns were repeated between 1.8 to 3.0 times. For audio alarm, increasing level 3 vibro-alarm was also the most difficult to memorize (2.8 times) while decreasing level 1 was the easiest to memorize (1.0 times). Other audio alarm patterns were repeated between 1.0 to 2.8 times. In the quiz given in the training stage, the average accuracy of vibro and audio alarms were 96.67% and 98.33% respectively. It indicated that the vibro-alarms were not difficult to recognize compared to sound cues.

In the 30-minute test with distraction, the average accuracy of recognizing vibro and audio alarm were 97.0% and 97.5% respectively. In both tests, subjects found that it was harder to recognize patterns with distraction. Also, both the vibro-alarm and audio alarm could grip their attention easily. Whenever there was an alarm, they had to stop what they were doing and pay attention on the alarm pattern. Compared with auditory alarm, they felt that the vibro-alarm was not as distracting as the auditory alarm and it was not more difficult to distinguish the patterns. They also thought that the beeping sound of the auditory alarm was very annoying.

All subjects said that it was quite difficult to distinguish the HR accurately in the vibro-feedback test; however, they were able to estimate the trend. From Figure 5, it was observed that subjects could closely follow the trend of HR change. The average error of recognizing the HR was around 20.13%. They also felt that the continuous vibration was quite annoying, but they found it tolerable.

Lastly, all subjects in the pseudo-data test preferred the vibro-alarm to the auditory alarm. They felt that keeping their listening ability open was important. However, they did not prefer to use the continuous feedback scheme on the device.

Average # of time each alarms need to be repeated before the subject memorize the alarm patterns			
		Vibro	**Audio**
Increasing	**Level 1**	2.60	1.80
	Level 2	2.40	2.40
	Level 3	3.00	2.80
Decreasing	**Level 1**	1.80	1.00
	Level 2	2.20	1.40
	Level 3	2.00	1.80
	Total	14.00	11.20

Average accuracy of vibro-alarm in training	96.67%
Average accuracy of audio-alarm in training	98.33%
Average accuracy of vibro-alarm in testing	97.00%
Average accuracy of audio-alarm in testing	97.50%
Average error for vibro-feedback scheme	20.13%

Table 1 shows the Phase I User Study result. Top: shows the average result of how well subjects can memorize the alarm patterns in Phase I User Study. Bottom: shows the average accuracy of using the vibro-alarm, audio-alarm and vibro-feedback scheme.

4.3.2 Analysis on Phase II Results – Clinical data

The results of testing the system on an anesthesiologist and on other subjects are similar. The subjects found that the vibro-alarm patterns were easy to remember and distinguish. From the training, it was noticed that increasing level 1 vibro-alarm was most difficult to

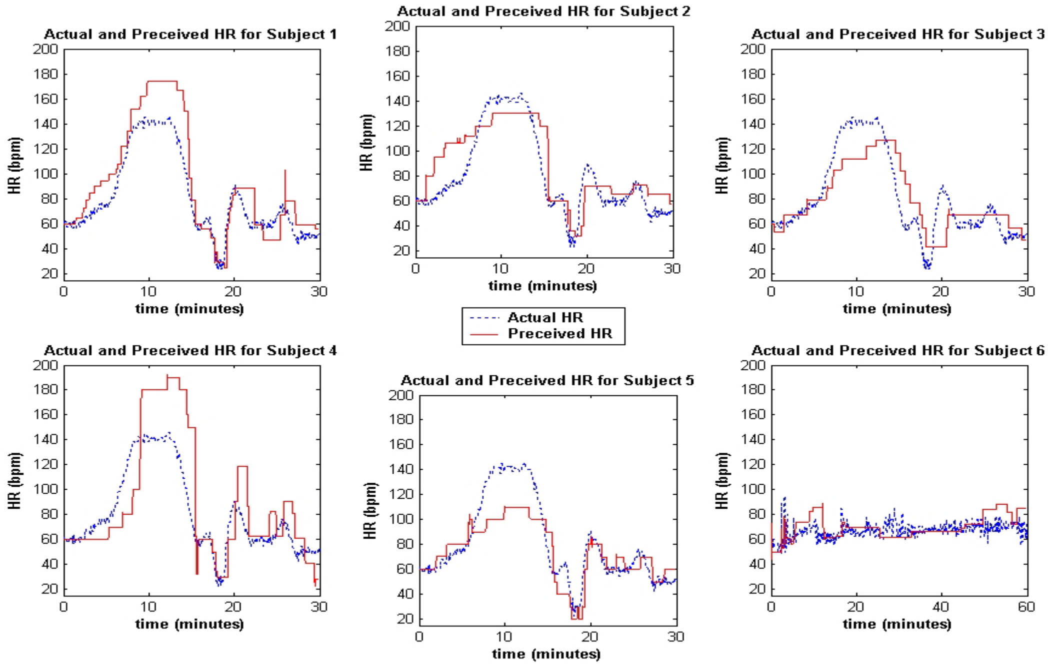

Figure 5 shows the results of the vibro-feedback tests of all subjects in phase I (subject 1-5) and II (subject 6) tests. The dotted line (blue) shows the actual HR; the solid line (red) shows the response of a subject. It was noticed that subjects could generally detect the HR changes; however, they could not really recognize the actual HR.

memorize (4 times) while decreasing level 3 was easiest to memorize (1 time). Other alarm patterns were repeated between 1 to 4 times. In total, the subject needed to feel 14 alarms before he could memorize all the alarm patterns.

In the one-hour clinical data test, the accuracy of recognizing vibro-alarm was 82.42% (as shown in Table 2.) The subject did not find it harder to recognize the pattern when he was distracted by the background music and the vibration was not a nuisance.

Similar to other subjects, the anesthesiologist sensed the change in HR (figure 5). However, he thought it was almost impossible to tell the current HR using the feedback scheme. The average error of recognizing the HR was around 10.44% (Table 2).

In contrast to other subjects, the anesthesiologist subject felt the feedback was comfortable. He also commented that, in the alarm scheme, the vibrotactile display was able to grab his attention every time. The audio alarm system in the operation room; however, tended to be ignored by him psychologically due to its '*unpleasant feeling*'.

4.3.3 Comfortability of Using Vibro-Monitor

Generally, subjects did not feel tired after using the vibro-alarm and they found that the device was light and comfortable to wear. However, two subjects indicated that their arms felt numb after the test. Moreover, the elastic band should not be too tight (they would feel numb) or too loose (the vibration would be less localized.)

Regarding the level of vibration, all subjects commented that the level of vibration was moderate, neither too weak nor too strong. No indication of adaptation was observed as none of the subjects found any changes in the amplitude of vibration and the alarm recognition error rate was always high. Also, all the subjects preferred the vibro-alarm scheme over the other schemes.

Number of learning times for vibro-alarms			
Increasing		**Decreasing**	
Level 1	4	**Level 1**	2
Level 2	1	**Level 2**	2
Level 3	3	**Level 3**	1
TOTAL		13	

Average accuracy of vibro-alarm in training (2 trials)	85.00%
Average accuracy of vibro-alarm in testing	82.42%
Average error for vibro-feedback scheme	10.44%

Table 2 shows the Phase II User Study result of an anesthesiologist (1-hr long clinical data.) Top: shows the average learning times of the vibro-alarms. Bottom: shows the average accuracy of using the vibro-alarm and the error in using the vibro-feedback scheme.

5 FUTURE WORK

Suggestion on future work on Vibro-Monitor includes optical isolating the device. The Vibro-Monitor regularly switches its motors on and off and its ground power needs to be separated from the rest of the operation room equipment. However, a ground potential difference would likely exist in such arrangement. When that happens, a phenomenon called ground looping may occur and garble the communication signals. The problem is solved by optically isolating the circuit.

Secondly, in the current alarm scheme, the length of the first burst is the same for all alarms although they are at different spatial locations. The location of the first burst describes the type of the alarm. One of the subjects suggested that the length of the first burst may be used to describe the level of the alarm as well. Subsequence short bursts of vibration can be used to confirm the level of HR status.

Lastly, all subjects indicated that the audio alarms were a hassle. One possible way of improving the existing system as well as the Vibro-Monitor is to integrate the audio-alarm and the Vibro-Monitor into one display system; utilizing the advantages of both systems to minimize their disadvantages.

6 CONCLUSION

We have implemented a new vibrotactile display that can be used as a silent display in an operation room. The display was capable of sending vibrations at 3 locations along the arm of an anesthesiologist to show HR status. This solved the noise problem presented in the existing auditory alarm systems.

Two vibrotactile stimulation schemes (vibro-alarm and vibro-feedback) were studied and compared against the audio system. It was found that the advantages of the vibro-alarm scheme were that it was not tired after use and the alarms were not annoying to the users. The study also found the vibro-feedback scheme tired after use, annoying to the user, and was hard to distinguish the absolute HR. The audio-alarm, on the other hand, was tired after use and annoying to the users. It was relatively easier to learn however. Finally, the study proved that the vibro-alarm scheme was the unanimous preference by all subjects.

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