Unconstrained noninvasive vital signs monitoring for detection of obstructive sleep apnea with automated prevention

Jonathan Waters
University of New Hampshire, Durham

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Abstract
The Bioengineering Laboratory at UNH has demonstrated the usefulness of medical device interoperability through previous work that involved connecting an advanced hospital bed with blood pressure monitors over an electrical communication bus known as Controller Area Network (CAN). The medical devices utilize the software communication protocol known as CANopen for communicating relevant patient data to one another. This thesis explores the opportunity to detect a person's heartbeat and respiration while lying in a hospital bed noninvasively and unconstrained for accurately identifying an episode of obstructive sleep apnea. The design and development of this device is a CANopen compatible therapeutic automatic bed adjustment to counteract a sleep apnea episode by restoring a person to normal respiratory sleep.

Keywords
Engineering, Electronics and Electrical, Engineering, Biomedical, Engineering, Computer
UNCONSTRAINED NONINVASIVE VITAL SIGNS MONITORING
FOR DETECTION OF OBSTRUCTIVE SLEEP APNEA WITH
AUTOMATED PREVENTION

BY

JONATHAN WATERS
B.S., University of New Hampshire, 2006

THESIS

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the Requirements for the Degree of

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in
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This thesis has been examined and approved.

Thesis Director, Dr. John R. LaCourse
Professor of Electrical and Computer Engineering
ECE Department Chair

Dr. Michael J. Carter
Associate Professor of Electrical and Computer Engineering

Dr. L. Gordon Kraft
Professor of Electrical and Computer Engineering

Dr. Wayne J. Smith
Lecturer of Electrical and Computer Engineering

Date
DEDICATION

This thesis is dedicated to my mother and father. Thank you for your constant love and support.
ACKNOWLEDGMENTS

First, I would like to thank my thesis advisor Dr. John R. LaCourse for his advice, guidance and patience throughout my graduate studies and during my thesis work.

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<tr>
<td>CPAP</td>
<td>Continuous Positive Airway Pressure</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>OSA</td>
<td>Obstructive Sleep Apnea</td>
</tr>
<tr>
<td>PCG</td>
<td>Phonocardiographic</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-to-digital Converter</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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</tbody>
</table>
ABSTRACT

UNCONSTRAINED NONINVASIVE VITAL SIGNS MONITORING
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University of New Hampshire, December, 2011

The Bioengineering Laboratory at UNH has demonstrated the usefulness of medical device interoperability through previous work that involved connecting an advanced hospital bed with blood pressure monitors over an electrical communication bus known as Controller Area Network (CAN). The medical devices utilize the software communication protocol known as CANopen for communicating relevant patient data to one another. This thesis explores the opportunity to detect a person’s heartbeat and respiration while lying in a hospital bed noninvasively and unconstrained for accurately identifying an episode of obstructive sleep apnea. The design and development of this device is a CANopen compatible therapeutic automatic bed adjustment to counteract a sleep apnea episode by restoring a person to normal respiratory sleep.
Vital sign monitoring is an important aspect of nearly all medical conditions and treatments. Heartbeat and respiration measurements are two critical vital signs that can be detected in a number of different ways. Most of the methods used in practice today are somewhat constrained and/or invasive to the patient [1], [12], [16], [18]. With advancements in technology, there are emerging methods that are able to detect heartbeat and respiration in unconstrained and noninvasive ways.

Detecting heartbeat and respiration in a noninvasive and unconstrained manner is beneficial for a number of reasons. The most obvious benefit of such a detection system is improved patient comfort. The detection systems in place currently require that the patient be connected to electrodes, cuffs, IVs and/or other constrictive and invasive devices. A second benefit to unconstrained and noninvasive monitoring is the ability for a health care professional to remotely monitor their patients. Detection devices today require that a health care professional be in the room checking a number of different devices [18]. An unconstrained and noninvasive monitoring system would allow for the health care professional to be removed from the room. Remote patient monitoring also allows for multiple patient monitoring. With the health care professional removed
from the patient’s room, they are able to monitor more patients quickly and efficiently, and then tend to those requiring immediate attention.

Of the numerous conditions related to respiration and heartbeat, one such condition is obstructive sleep apnea syndrome. Obstructive sleep apnea is one of the most common syndromes in America, affecting about 18 million Americans [11]. Obstructive sleep apnea is a respiratory condition that causes a patient to stop breathing while they are asleep. Obstructive sleep apnea also has adverse effects on heartbeat and can cause high blood pressure [1], [11]. Left untreated, obstructive sleep apnea can lead to a number of health problems, including death [11]. There are a number of methods for detecting obstructive sleep apnea, but due to the invasive and constricting nature of respiration monitoring, they can be unpleasant. A noninvasive and unconstrained heartbeat and respiration monitor could be beneficial for people with obstructive sleep apnea.

This thesis proposes an unconstrained and noninvasive system that will measure a person’s respiration rate while lying in a hospital bed. The system will be able to detect apneic events in the person’s respiration pattern, and furthermore, when connected to an advanced medical bed, will be able to utilize the bed to provide a first response positional treatment to the apneic events.
CHAPTER II

BACKGROUND

2.1 Noninvasive Unconstrained Heartbeat and Respiration Detection

In order to determine an effective detection method for heartbeat and respiration periods, a number of previous methods are reviewed. The area of unconstrained and noninvasive monitoring has produced some significant research recently.

One way to monitor a patient's heartbeat and respiration periods noninvasively is through the use of an acoustic sensor. Matsubara and Tanaka used an acoustic sensor enclosed in an air pillow under a patient's head [2]. In their work, they obtained a vibration signal from the output of the acoustic sensor that contained information about the heartbeat and respiration of the subject under monitoring. They first applied a bandpass filter to the output of the sensor, and then used Kalman filters along with maximum likelihood estimation to measure the patient's instantaneous heartbeat and respiration period.

The signal processing method Matsubara and Tanaka use in their paper takes into account that the output from the acoustic sensor is essentially a combined signal containing heartbeat and respiration information. They first applied a full-wave rectification of the sensor output to a fourth order Butterworth band pass filter with cutoff frequencies of 0.5Hz and 2.0Hz.
Matsubara and Tanaka then created a dynamic model of the system that includes the three frequency components of their measured signal output. They create the necessary Kalman filter equations to estimate the heartbeat and respiration periods from the acoustic sensor delta. However, they point out that the frequency components of their dynamic model are initially unknown, and therefore the Kalman filter cannot be applied directly. Therefore, Matsubara and Tanaka utilize a maximum likelihood estimation procedure for determining the actual patient's heartbeat and respiration period.

The results of Matsubara and Tanaka's work were encouraging. They compared their system with the measurements of a thermistor and an electrocardiograph. The thermistor is used to measure a patient's respiration period, and the electrocardiograph measures a patient's heartbeat period [2] [15]. The average error for the heartbeat period measurement between the electrocardiograph and their system was 1.0%. The average error for the respiration period measurement between the thermistor and their system was 11.4%. The respiration measurement did not do as well as the heartbeat measurement because the acoustically sensed respiration signal is very small.

This method for detecting heartbeat and respiration seems to be effective, but the respiration measurement error could be improved. The acoustic sensor was enclosed in an air pillow, but no experiments were conducted with the sensor placed in another location, like beneath the subject's thorax. A different
sensor placement might improve the respiration rate estimate error, as well as the heartbeat error, which was quite good already.

Another unconstrained and noninvasive method for measuring heartbeat and respiration is through the use of a phonocardiographic (PCG) sensor. A PCG sensor is an acceleration sensor that measures vibrations. In Tanaka et al., a PCG sensor is placed on a water mat that is beneath a patient’s thorax [15]. The sensor is able to detect the vibrations on the water mat caused by the patient’s heartbeat and by the patient’s respiration. Tanaka et al. use digital signal processing techniques on the output of the sensor to estimate instantaneous and average heartbeat period, as well as instantaneous and average respiration period.

In their paper, heartbeat periodicity is obtained from the autocorrelation function; however, the autocorrelation function cannot be directly applied to the output of the sensor because the essential value will be cancelled out due to differences in the periodicities of the signal at different times caused by vibration. The output of the PCG sensor must first undergo a full wave rectification of the vibratory signal. Then a fourth order bandpass Butterworth filter is applied to the signal with cutoff frequencies 0.7Hz and 2Hz. These cutoff values for the filter were used because the heart beats in a range of 50 to 100 beats per minute. After the bandpass filter is applied the autocorrelation function can be estimated and the average heartbeat period can be obtained.
In a similar fashion, Tanaka et al. was able to extract the respiration period from the PCG sensor output. The PCG sensor output is modulated by the respiration through the tension of the surface the subject was lying on, because the PCG sensor was attached to this surface. Therefore, the respiration period can be measured from the envelope of the sensor output. As with the heartbeat period measurements, a bandpass filter was applied to the fully rectified output of the sensor, except that the respiration filter used cutoff frequencies of 0.1 Hz and 0.4 Hz. The cutoffs here are lower because the typical respiration rate is lower, in the range of about 12 to 20 breaths per minute.

The results of the measurement using the PCG sensor were quite good for the heartbeat period measurement. In the twelve subjects involved in the experiment, there was less than a 1% error in both the mean and the standard deviation when compared with the electrocardiograph measurements used as a reference. The results were not quite as good for the respiration measurement, with a range of about 0.5 – 4% error when compared to a thermistor-type respiration pickup as a reference. The authors contributed the higher percent error in respiration measurements to a low signal-to-noise ratio as well as issues with the thermistor-type pickup; however, they did state that the measurement accuracy is sufficient from a clinical aspect.

This type of sensor seems to have a better error rate than the sensor method proposed in Matsubara and Tanaka. The sensor is of a different type,
and the placement is more appropriate because measurements are taken closer to the thorax of the subject.

In a paper by Watanabe et al. in 2005, respiration and heartbeat rates were measured in a noninvasive and unconstrained way through the use of a pressure sensor [6]. This pneumatic method involves an air-sealed cushion positioned between the bed mattress and the bed frame. The pressure sensor detects pressure changes in the air mattress caused by a person’s heartbeat and respiration. The sensor output is processed through different filters with different bandpass frequencies to distinguish between heartbeat and respiration rates. The output from the filters is run through a signal processing element that computes the 512 point Fast Fourier Transform (FFT) which is then able to determine the heartbeat and number of respirations per minute.

To verify their system, a polygraph was used as the control for measuring ECG to compare with their heartbeat measurements, and a belt-type respirometer was used as the control for measuring respiration to compare with their respiration measurements. Watanabe et al. used a signal-to-noise ratio calculation as a reliability index. The signal-to-noise ratio was calculated by observing the signal as the peak of the spectrum of the FFT of the filter output, and the noise as the average value of the spectrum components excluding the fundamental and higher components of the spectrum. They performed numerous tests with varying signal-to-noise ratios ranging from 32.1 dB down to 9.5 dB. For their heartbeat measurements, it was shown that they could
accurately identify heartbeat when the signal-to-noise ratio was greater than 12 dB. However, when the signal-to-noise ratio dropped below 12 dB, the heartbeat measurement was off by 1 when compared with the polygraph. They determined that as long as the signal-to-noise ratio was greater than 12-13 dB, their measurements would be reliable.

Watanabe et al. ran their system through a variety of tests to determine not only the accuracy of their system for measuring heartbeat and respiration rate, but to determine the reliability of their system under different conditions. For measurement accuracy, a bench test was carried out over a short period of about one minute. They calculated signal-to-noise ratios for different body postures (supine, lateral, and prone), different sensor positions (head, back/breast, and hip/thigh), and different subjects (ranging from 8 to 46 years old and 28 to 102 kg). In all of the tests the respiration rate and heartbeat rate were clearly measured, and no signal-to-noise ratio was below 13 dB, thus indicating reliable measurements. One of the interesting results from this bench test was that the system accurately measured the heartbeat and respiration rate whether the subject was lying in the supine, lateral, or prone position.

To verify the feasibility of using this system for overnight measurements, Watanabe et al. monitored 15 subjects overnight with their system for measuring heartbeat rate as well as the polygraph. They calculated the percent frequency of correctly estimated heartbeats for all the samplings in the overnight measurements, and found that they correctly estimated as high as 96.7%, and as
low as 67.5%. Only three subjects were below 80% accurate, and the authors attributed this inaccuracy to the “first night effect”, where subjects were moving very frequently and caused the signal-to-noise ratio to drop below the threshold.

While the majority of the testing of this system was in regard to the heartbeat rate measurement, it is assumed that the respiration rate measurements would be similar. Both heartbeat rate and respiration rate were measured accurately in the short period tests, and even cessations in respiration were observed accurately. This pneumatic based system for measuring heartbeat and respiration rate seems to perform well, and is one of the few systems that show accurate measurements when the subject is in a variety of positions.

Wantanbe et al. went beyond the experiments of the previous papers to extend their measurement experiments to include measurements based on various patient body postures, as well as various sensor placements. The system seemed to be the most accurate to date, but still suffered measurement inaccuracies when a subject was changing body posture. An encouraging aspect of this system was that there were specific results for a patient that induced apneic events by holding his breath, and the apneic events were correctly identified.

Similarly to Watanabe et al., Kimura et al. [4] use pressure in measuring heartbeat and respiration. However, instead of an air mattress with an air pressure sensor, they use a pad of electrically conductive fibers as temperature
sensors. These fibers, when used in a sandwich structure by overlaying one strip on top of another with a nonconductive material in between, will make a pressure sensor when the two strips connect through the nonconductive material.

Kimura et al. constructed a sensor sheet of these electrically conductive fiber strips in a grid like fashion. The sheet is connected to some sensor controllers that are able to choose one particular sensor from the sheet, and all of the sensor signals are passed into an output controller connected to a computer. The sensor data contains three signals: a DC component, a very low frequency component for respiration, and a third frequency component for heartbeat. The sensor data was run through appropriate filters, with band pass ranges of 0.16 – 0.6 Hz and 0.8 – 1.6 Hz for respiration and heartbeat, respectively.

In addition to measuring heartbeat and respiration, this sensor sheet is also able to detect patient posture through the DC component of the sensor data. Through a posture recognition algorithm, Kimura et al. were able to correctly distinguish between the prone, supine, left and right lateral postures. They were also able to use the posture recognition algorithm along with the sensor controllers to determine and then isolate which sensor would be ideal for picking up heartbeat and respiration.

The medical devices used to verify their measurements are not identified specifically, only noting that they did measure heartbeat and respiration with a “conventional medical device.” Over a ten minute period, the error between their measurements and the conventional medical device was less than 0.5%. They
then proceeded to make measurements over a seven hour period where their subject was sleeping. They did not use the conventional medical device during this measurement period, as they were satisfied with their previous results, but wanted to verify their posture detection algorithm. The postures were categorized into four kinds; prone, supine, right lateral, and left lateral. A video camera was used to verify the subjects sleeping posture, and the posture was correctly identified 90% of the time. It was noted, however, that there were times when their measurement system was unable to capture the data due to small motions of the body. During stable sleeping, which typically constituted 95% of the overall sleeping period, their heartbeat and respiration measurements were accurate.

The system proposed by Kimura et al. appears to be very accurate in measuring heartbeat and respiration. However the method by which they calculated their error percentage is vague as they do not explicitly mention the actual equipment used to verify their results. The biggest benefit of the sensor sheet system proposed by them is the ability to identify patient body posture. As in the other methods to detect heartbeat and respiration, this system is able to do so regardless of body posture, but is also able to distinguish what position the subject is in at all times.
2.2 Obstructive Sleep Apnea

Obstructive sleep apnea is a respiratory disorder in which a person will stop breathing while sleeping. These periods where normal respiration and breathing are stopped are called apneic events. A person with obstructive sleep apnea will typically experience hundreds of apneic events a night and each one lasts for about 10 seconds, and can be as long as a minute [1].

Obstructive sleep apnea affects about 18 million Americans, and many more people suffer from the disorder and have not been diagnosed [11]. Besides the obvious danger of respiration failure while sleeping, obstructive sleep apnea has other serious effects on a person's health. Studies have shown that obstructive sleep apnea can lead to high blood pressure, coronary artery disease, heart attacks, and even strokes [1], [16], [18].

There are many treatments for patients suffering from obstructive sleep apnea [1], [8]. The treatment method is usually dependent on the severity of the syndrome. The most common form of treatment is known as continuous positive airflow pressure (CPAP). This type of treatment involves a mask placed over the face of the patient that is connected to a machine that delivers continuous air pressure to prevent the tissues in the nose and throat from collapsing and obstructing the airway. This type of treatment is beneficial and very effective when used properly, but not very comfortable.

There are a number of adverse side effects related to CPAP. The most common complaint from patients with obstructive sleep apnea that are
undergoing CPAP is irritation in the nose and throat [1]. The continuous air pressure can cause nasal congestion as well as a sore and dry mouth. Other reported side effects include a feeling of claustrophobia, and chest muscle discomfort. These side effects and others can lead patients to stop using the CPAP device, and long term compliance with CPAP systems is low, with about one third of patients who stop using the device [1].

In a report on obstructive sleep apnea [1], sleeping in the supine position was found to cause apneic events in about half of all people with mild sleep apnea. It was found that a patient's body position can greatly affect the number, and the severity of apneic events. The report stated that at least twice as many apneic events occurred in people lying in the supine position compared to those lying in the lateral position. In fact, patients that sleep in the supine position and experience 50 to 80 apneic events per hour can sometimes nearly eliminate all of the apneic events by moving to the lateral position.

The findings related to sleep position in obstructive sleep apnea have led to another form of treatment known as positional therapy. Some treatments in this area involve placing items on one side of the bed so as to prevent the patient from sleeping in the supine position. This type of treatment does not work as effectively as CPAP in patients with more severe OSA; however, some studies have indicated that laying in the lateral position as opposed to the supine position can help alleviate OSA in patients with more mild cases [13], [14].
A study in 2005 aimed to determine how common positional sleep apnea was amongst obstructive sleep apnea patients [7]. In this study, it was found that of the 248 patients with obstructive sleep apnea, 68 (27.4%) were defined as suffering from positional sleep apnea. The 248 patients were divided into three categories of severity of obstructive sleep apnea; mild, moderate, and severe. Of the patients suffering from mild obstructive sleep apnea, 49.5% were identified as having positional sleep apnea, which was the highest of the three. 19.4% of patients with moderate obstructive sleep apnea and 6.5% of patients with severe sleep apnea were identified as suffering from positional sleep apnea.

While not all people with obstructive sleep apnea will decrease their apneic events by sleeping in a non-supine position, the overwhelming conclusion is that this sleep position can prevent the apneic events in a significant number of people.

2.3 CANopen Protocol

CANopen is a communication protocol and device profile specification for embedded systems that allows for automatic, reliable communication and control between devices. In terms of the Open Systems Interconnection Reference Model (OSI), CANopen specifies layers 3 through 7, and is standardized on the CAN physical layer. CANopen is based on a communication profile, which specifies and defines the underlying communication mechanisms. Additionally, the CANopen standard specifies an application layer that is defined by a device
A wide variety of devices used in industrial automation (digital and analog I/O modules, drives, controllers, programmable devices) are all described by CANopen device profiles. A device profile describes the functionality of a specific device.

The CANopen communication protocol specifies that each device must have a CANopen object dictionary. The object dictionary is an array of variables that are used to configure the device as well as contain measurement data. Each variable in the object dictionary has a unique index associated with it. The basic structure for the standard object dictionary is shown in Table 2.1.

<table>
<thead>
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<th>Index (hex)</th>
<th>Type Description</th>
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<tr>
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<td>Reserved</td>
</tr>
<tr>
<td>0x0001 - 0x001F</td>
<td>Static Data Types</td>
</tr>
<tr>
<td>0x0020 - 0x003F</td>
<td>Complex Data Types</td>
</tr>
<tr>
<td>0x0040 - 0x005F</td>
<td>Manufacturer Specific Data</td>
</tr>
<tr>
<td>0x0060 - 0x007F</td>
<td>Device Profile Specific Static Data Types</td>
</tr>
<tr>
<td>0x0080 - 0x009F</td>
<td>Device Profile Specific Complex Data Types</td>
</tr>
<tr>
<td>0x00A0 - 0x00FF</td>
<td>Reserved</td>
</tr>
<tr>
<td>0x1000 - 0x1FFF</td>
<td>Communication Profile Area</td>
</tr>
<tr>
<td>0x2000 - 0x5FFF</td>
<td>Manufacturer Specific Profile Area</td>
</tr>
<tr>
<td>0x6000 - 0x9FFF</td>
<td>Standardized Device Profile Area</td>
</tr>
<tr>
<td>0xA000 - 0xFFFF</td>
<td>Reserved</td>
</tr>
</tbody>
</table>

Table 2.1 CANopen Object Dictionary Layout

The variables in the object dictionary are accessed in one of two ways. There is a Service Data Object (SDO) protocol which is a server/client relationship used for setting and reading values from the object dictionary. There is also a Process Data Object (PDO) protocol used to process real time data among the CANopen nodes in a network. The CANopen Device Model is shown in Figure 2.1.
Previous research in the Bioengineering Laboratory at the University of New Hampshire has attempted to prove the usefulness of CANopen outside of the industrial automation field, by working to create new device profiles for medical devices. Some medical devices, like hospital beds, are already using CANopen internally for devices like sensors, motors, and drives. The research at UNH hoped to define an entire medical device as a CANopen device profile, which would allow for different medical devices to communicate with one another, and achieve a new level of interoperability.
One such project involved an invasive blood pressure monitor and a hospital bed. The two devices were connected to microcontrollers running the CANopen protocol stack and communicated information to one another for automatic control. The hospital bed would send information regarding patient position in the bed, and the blood pressure monitor would send information regarding patient's blood pressure. It is a known problem in the medical community that when a patient is elevated or lowered from their initial position in a hospital bed, the invasive blood pressure monitor will register inaccurate readings due to the pressure change in the monitoring equipment. The system designed at the University of New Hampshire automatically adjusted the blood pressure monitor to display the correct blood pressure of the patient based on any elevation changes that occurred in the hospital bed [5].

Another implementation of CANopen in medical devices developed at the University of New Hampshire involved a noninvasive blood pressure monitor and a hospital bed. In this system, the hospital bed would automatically adjust itself based on the patient's blood pressure measured by the noninvasive monitor. The hospital bed would move to either a head elevated, or foot elevated position to help alleviate high or low blood pressure, respectively [19].

With the significant number of obstructive sleep apnea patients suffering from positional sleep apnea, an automated system to promote sleeping in the lateral position could help alleviate apneic events. A noninvasive and unconstrained respiration detection method would allow for the patient to sleep
uninhibited by other constrained and invasive devices for treating OSA. The CANopen protocol has been proven to perform well in automated control of medical devices, and would work well with integrating a noninvasive and unconstrained respiration detection device with a hospital bed equipped with a patient roll feature.

2.4 Proposed System

The research described here involves the design and development of a noninvasive and unconstrained device that detects a person's heartbeat and respiration while lying in a hospital bed. The device is designed to accurately identify when a person is experiencing apneic events. Furthermore, the device is CANopen compatible and can connect to a CANopen compatible hospital bed to provide an automatic bed adjustment for a subject suffering an apnea.

The main feature of the device is the ability to measure heartbeat and respiration in a noninvasive and unconstrained manner. Of the methods reviewed for detecting heartbeat and respiration, the most appropriate for the research proposed here is a pneumatic approach through the use of a pressure sensor. Previous work involving heartbeat and respiration detection with a pressure sensor proved to be extremely accurate not only when the subject was lying in the supine position, but also in the prone and lateral positions.

The heartbeat and respiration signals detected from the device are computed and stored in a microcontroller. The microcontroller runs the
CANopen protocol stack, and in addition to performing digital signal processing (DSP) on the detected signals, is also serves as the gateway between the vital signs detection device and the hospital bed.

With the hospital bed and the vital signs detection device both CANopen compatible, they are able to communicate with one another. The detection device sends information regarding patient respiration patterns, and the hospital bed provides information regarding bed position and control. The detection device serves as a processing unit that makes determinations about bed movements.

Most hospital beds already come equipped with a patient roll feature to assist health care providers in turning patients. When the device detects that a patient is suffering from obstructive sleep apnea, the device will communicate CANopen messages directly to the hospital bed to automatically utilize the patient roll feature to reposition the patient into the lateral position to help alleviate the apnea. A block diagram of the overall proposed system is shown in Figure 2.2.
The goal of the proposed system is to serve as an automated first response mechanism for a physician to use as treatment for patients with obstructive sleep apnea. With the aid of the CANopen network, the physician will be able to program in various treatment methods customized to the patient's needs. Through the use of a graphical user interface (GUI), the physician or caregiver will be able to set parameters like the specific bed adjustment to be made when an apnea is observed, and the amount of time without patient respiration before the bed makes an automated adjustment.
CHAPTER III

MATERIALS AND METHODS

3.1 Pneumatic Measurement Method

The Bioengineering Laboratory has a modern hospital bed (Stryker Go Bed II), which contains an accessible air bladder on the upper portion of the mattress where a patient's torso would rest. This feature of the hospital bed suggested implementing a similar approach to the method proposed in Watanabe et al. where a pressure transducer was used to measure pressure changes caused by vital functions in an enclosed air mattress.

The air bladder is filled by an air compressor that is part of the hospital bed. In order to measure the pressure within the air bladder, the hose connecting the bladder to the compressor was disconnected, and the pressure transducer was attached to the end of the hose.

The same pressure transducer used in the paper by Watanabe et al. was acquired for this research. The specific pressure transducer is model S11-M2 from Primo Microphones GmbH, and can be seen in Figure 3.1. As noted in Watanabe et al., the transducer has a sensitivity of 56mV/Pa. Given the voltage range of the analog-to-digital converter (ADC) on the proposed system's microcontroller of 0 to 5.12V, this sensitivity is more than adequate for detecting
the minor pressure fluctuations caused by a human’s heartbeat and respiration patterns

To ensure an air tight seal between the end of the air bladder’s hose and the pressure transducer, some Polyvinyl Chloride (PVC) bonding tape was used around the threaded portion of the air hose. The air hose was then screwed to a valve onto which a narrow piece of plastic tubing was fitted. This piece of tubing was the appropriate diameter into which to insert the pressure transducer, and thus an airtight path from the air bladder to the pressure transducer was

Figure 3.1 Pressure Transducer
achieved. The complete assembly of the pressure sensor to the air hose can be seen in Figure 3.2.

![Figure 3.2 Transducer Interface with Air Bladder](image)

**3.2 Circuit Design**

The sensitivity of the pressure transducer is 56mV/Pa, and the pressure level of the respiration vital sign is in the range of 0.2 to 2 Pa [6]. Therefore the typical output range is just a few millivolts. The microprocessor used for filtering the data has a 10-bit ADC that can accept voltages in the range of 0 to 5.12V; therefore, an amplifier was designed to increase the signal level to the 0 to 5 Volt range.
range. Additionally the circuit will need to remove the DC bias that is generated when providing power to the transducer.

Since the respiration vital sign is more directly affected by obstructive sleep apnea than heart rate, the circuit was designed to maximize the range of the respiration signal in the ADC. The pressure changes caused by heartbeat are significantly less amplified than the pressure changes caused by respiration. Therefore, by designing the circuit to capture the full range of the respiration signal, much of the necessary data in the heartbeat signal was lost. The heartbeat’s low amplitude fluctuations in the 0 to 5.12V range, combined with only 10 bits available on the microprocessor’s ADC, made it infeasible to accurately identify the heartbeat signal from the pressure measurements.

The first stage of the circuit, as shown in Figure 3.3, uses a capacitor to remove the DC bias from the output of the transducer. This causes only the AC fluctuations from the pressure transducer to be passed.

![Figure 3.3 Capacitor Filtering](image-url)
The second stage of the circuit, as shown in Figure 3.4, consists of a non-inverting operational amplifier that is used to amplify the AC voltage of the signal. The result after this stage is an amplified signal centered about 0V.

![Figure 3.4 Amplification](image)

For use in the microprocessor, the signal must be biased up to 2.5V so that the entire signal falls in the range of 0 to 5.12V. The third stage of the filter, as shown in Figure 3.5, accomplishes this by using another non-inverting operational amplifier with feedback to the negative input.
To implement the complete circuit, an LM358N was chosen as the operational amplifier. This operational amplifier is a low power dual operational amplifier, so it provides the two non-inverting operational amplifiers needed for the circuit. The designed circuit was implemented on a breadboard. A functional block diagram of the circuit can be seen in Figure 3.6.
3.3 Analog to Digital Conversion

In order to evaluate and manipulate the raw voltages produced by the pressure transducer, the measurements need to be converted from the analog domain to the digital domain. The pressure transducer converts the air pressure exerted on the transducer into an electrical signal. This electrical signal is a continuous analog signal, and a computer requires the analog signal to be converted into a discrete, digital representation. Once a digital representation of
the pressure measurements is obtained, the voltage readings can be analyzed in a computer, and ultimately processed in a microcontroller.

Viewing the voltage readings output by the pressure transducer on a computer is desirable for a number of reasons. The first reason is to easily verify that the pressure transducer is functional and operating correctly. The computer also has software tools that aid in the signal analysis process, as well as any digital filter design that is necessary. Another benefit to working with the pressure transducer’s output in a computer is to be able to quickly record and save measurements made over a long period of time, and store them for access at a later date without needing to re-conduct the experiment. Finally, the proposed system will ultimately call for the pressure measurements to be processed and stored in an embedded microcontroller, and this will require an analog to digital conversion process as well.

To verify that the pressure transducer connected to the air bladder on the hospital bed was functioning properly and detecting vital signs, a USB ADC device was used to interface to the computer. The specific device is made by National Instruments (NI USB-6008) and can be seen in Figure 3.7.
This device also comes with a software program made by National Instruments, commonly used in signal analysis, called LabVIEW. The NI USB-6008 has 8 analog input ports, and a USB connection that connects to the USB input port of a computer. The output from the pressure transducer circuit was connected to one of the analog inputs of the NI USB-6008. The LabVIEW software was set to sample the data at 100 MHz which more than satisfies the Nyquist sampling theorem for the low frequency heartbeat and respiration signals.

The software captured the pressure signal data on the analog input port and further inspection of the digital output data showed a clear indication that the respiration waveform was captured. As expected, the respiration waveform was corrupted by higher frequency noise generated from the hospital bed. The noisy
output from the pressure transducer captured with the LabVIEW software was used offline to design an appropriate filter for the respiration waveform.

3.4 Filter Design

A typical resting adult's respiration rate will range from 12 to 20 breaths per minute [15]. This corresponds to a range of about 0.2 to 0.33 breaths per second, or a frequency of 0.2 to 0.33 Hz. The filter designed to extract the respiration waveform from the output of the pressure transducer was designed for a normal adult's typical resting conditions. Based on these respiration characteristics and the success of previous research for respiration filter designs, the filter designed for this thesis was a $4^{th}$ order Butterworth band-pass filter with a frequency range of 0.1 – 0.4 Hz. The Butterworth filter is mathematically designed to have the best performance for passing the frequencies in the passband, which is ideal for this implementation.

After capturing the output from the pressure transducer circuit and converting the data to the digital domain, the digital data was stored in a text file for use in the software program MATLAB. MATLAB's Filter Design Toolbox was then used to aid in the design of the filter coefficients. The resulting filter is an IIR filter with 9 filter coefficients.

To gauge the performance of the filter, a short trial was performed on a test subject. The subject laid on the hospital bed, and the pressure measurements were recorded by LabView using the NI USB-6008. The resulting
data was imported into MATLAB and tested with the designed filter. The original data without filtering can be seen in Figure 3.8, and the result after the data was processed through the filter can be seen in Figure 3.9.

Figure 3.8 Non-filtered Respiration Measurements
3.5 Implementation on an Embedded Microprocessor

The hospital bed in the Bioengineering Laboratory has many sensors and motors that allow the bed to perform many advanced bed functions such as: measure a patient’s weight, inflate or deflate the air mattress, and adjust the height and tilt of the bed. All of the electronic components of the hospital bed communicate messages internally over CAN using the CANopen protocol.

To develop a device with the capability to measure a patient’s respiration rate and communicate this data over the CANopen network, a microprocessor is
needed. The microprocessor must have an integrated CAN controller, and in addition this microprocessor must have the CANopen software protocol stack ported to it. Also, the microprocessor must have an ADC to be able to convert the analog voltage readings from the pressure transducer and manipulate and store the data digitally.

The Embedded Microprocessor Design course (ECE649) at UNH uses an Axiom CML12S-DP256 Development Board that has a Freescale HCS12 microprocessor, specifically the MC9SDP12DP256B. The Freescale processor on this development board has an integrated CAN controller and has previously been used for other CANopen projects in the Bioengineering Laboratory, so the CANopen software protocol stack has already been adapted to it. There is also an 8 channel 8/10-bit ADC, so this processor is ideal for this thesis.

To preserve as much precision as possible in the analog to digital conversion of the pressure transducer output, the microprocessor’s ADC was configured to operate in 10-bit mode. Only one channel is needed, so the appropriate registers were configured so that an interrupt would be triggered by channel 0. An interrupt service routine was written to store the 10-bit digital pressure values.

Within the application space of the CANopen protocol stack, a routine was written that would filter the noisy digital pressure values based on the previously designed MATLAB filter. This routine would produce a new filtered value that accurately represents a subject’s respiration waveform.
This respiration waveform value is then fed to another routine that was written to determine peaks within the waveform. The routine was first designed in MATLAB, and then implemented on the microprocessor. The code used for the peak detection algorithm can be found in Appendix A.

The peak detection routine compares each current filtered value to the previously stored maximum filtered value to determine if a new maximum value has been found. A timestamp is also stored and associated with each maximum value. When a new maximum value is found, the associated timestamp is subtracted from the previous maximum value's timestamp, and the result is a calculated value for the seconds between subsequent breaths. This calculated value for seconds per breath can be inverted and multiplied by sixty seconds to determine the instantaneous respiration rate in breaths per minute.

MATLAB was used to verify the peak detection algorithm using the same short trial data used to verify the performance of the filter. The calculated peaks in the filtered respiration waveform were plotted on top of the graph of the waveform and the result can be seen in Figure 3.10.
3.6 CANopen Object Dictionary

The operation of the various sensors, motors, and drives of the hospital bed is controlled by the CANopen protocol. Each of the devices that make up the hospital bed has an object dictionary that describes the information that each device contains. Furthermore, the object dictionary for each device specifies how the device should react to messages it receives from other devices. The embedded microprocessor will be an additional device that comprises the complete hospital bed, and another device that is communicating on the
CANopen network. In order for the device to communicate with the other devices within the bed, a CANopen object dictionary must be defined and implemented.

The CANopen object dictionary for the embedded microprocessor stores the measured digital pressure readings output from the pressure transducer, the computed filtered pressure readings, the calculated respiration rate, and the location of these values in the object dictionary so that other devices on the CANopen network may interact with them. These values are all calculated from the implemented routines described in section 3.5. The values are stored in the Standardized Device Profile Area of the object dictionary, and can be seen in Table 3.1.

<table>
<thead>
<tr>
<th>Index</th>
<th>SubIndex</th>
<th>Variable</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x6001</td>
<td>0x00</td>
<td>ATD Value</td>
<td>SIGNED32</td>
</tr>
<tr>
<td>0x6002</td>
<td>0x00</td>
<td>Respiration Waveform</td>
<td>SIGNED32</td>
</tr>
<tr>
<td>0x6003</td>
<td>0x00</td>
<td>Instantaneous Respiration Rate</td>
<td>UNSIGNED8</td>
</tr>
<tr>
<td>0x6004</td>
<td>0x00</td>
<td>Apnea Window</td>
<td>UNSIGNED8</td>
</tr>
</tbody>
</table>

Table 3.1 Device Profile Object Dictionary Entries

The object dictionary also specifies that these stored values should be output in 3 transmit PDOs at a frequency of 100 Hz. The specification of the PDOs is primarily used for testing and verification for this thesis, but in the future they may be utilized by other devices on the CANopen network in some new way. The transmit PDO mapping can be seen in Table 3.2.
3.7 Hospital Bed Movement Capabilities

Originally, it was desired to use the turn-and-assist feature of the Stryker Go Bed II hospital bed that would inflate one side of the bed mattress resulting in the subject being rolled into the lateral sleeping position. This was desired because of previous research indicating a decrease in apneic events amongst patients with OSA when sleeping in a lateral position [13], [14]. Unfortunately, the Go Bed II turn-and-assist feature is not a feature that communicates over the CAN bus, and therefore does not interact with the other CANopen units of the bed, and in fact has no way of being manipulated.

The purpose of this thesis, though, is to show that a first response bed movement can be triggered. Therefore, a different bed movement function that does communicate over the CAN bus and can be manipulated by CANopen was used. The new bed movement function is the known as the assisted trendelenburg feature.

The assisted trendelenburg feature of the hospital bed is a feature that causes the subject to be placed into the trendelenburg position, which is the position where the subject’s feet are raised higher than the head. This feature
can be accessed over the CAN bus, so when the subject is suffering an apnea, and the microprocessor is no longer detecting respiration peaks, a CANopen PDO is issued to the bed to begin raising the patient's feet above the head.

Despite the inability to utilize the originally intended feature of the hospital bed, which coincided with research for preventing apneic events, the actual system still proves that it is possible to automatically trigger a bed movement in response to a subject suffering obstructive sleep apnea.

### 3.8 CANopen Application

The main CANopen application for this thesis utilizes the data in the CANopen object dictionary, as well as the knowledge of the other hospital bed devices' CANopen object dictionaries to control the movement of the hospital bed in a meaningful way. As previously mentioned, the bed movement that is triggered is the assisted trendelenburg feature of the hospital bed.

The assisted trendelenburg feature can be triggered by issuing an SDO write to the hospital bed object dictionary entry 0x609E on node 32. This object dictionary entry is for the footboard control panel. There are numerous buttons on the footboard of the hospital bed, and values written into entry 0x609E simulate button presses on the footboard. Specifically, the value 0x20000 simulates the pressing of the button to begin the assisted trendelenburg feature.

The CANopen application stores a timestamp when a peak is detected in the peak detection algorithm. Upon detection of subsequent peaks, the
application calculates the difference between the timestamps, and stores the result as the instantaneous respiration rate. Additionally, the application constantly calculates the difference between the timestamp of the last stored peak, and the current time. If this difference is greater than the value defined for the Apnea Window, then the application issues an SDO write of 0x20000 to object dictionary entry 0x609E on node 32, and the bed movement is triggered.
CHAPTER IV

EXPERIMENTS AND TESTING

4.1 System Verification

The system verification process was implemented in two stages. Before experiments could be conducted to test the automatic bed movement in response to detected apneic events, an experiment was required to ensure that the respiration rate was being accurately measured through the air bladder via the pressure transducer. To verify that the respiration rate was being measured accurately, a thermistor was used in a Wheatstone bridge as the control for the respiration waveform. Previous research papers have used the thermistor as an accurate control for comparing measured respiration waveforms [2], [15], [18], so this method was also employed in this thesis.

A thermistor is a resistor that has a resistance that varies with temperature. When incorporated in a Wheatstone bridge, the thermistor can be used to generate a voltage waveform that varies according to the temperature fluctuations near the thermistor. For respiration detection, the thermistor is placed in or around the mouth and nostrils so that temperature changes caused by breathing patterns can be measured. The Wheatstone bridge circuit can be seen in Figure 4.1.
In the above circuit diagram, the resistance of $R_7$, $R_8$ and $R_9$ are known and constant, and the thermistor is variable. As the thermistor varies, the voltage measured between points A and B varies. The output from points A and B are connected to the NI USB-6008 ADC for measurement and analysis in a computer. Using the software that comes with the NI USB-6008, the analog voltage generated in the Wheatstone bridge can easily be captured and stored digitally in the computer for offline analysis.

Additionally, the application on the microprocessor outputs the filtered measured respiration data calculated from the pressure transducer every ten milliseconds in transmit PDO2. This data is available on the CAN bus for use by other applications and devices. For analysis and verification purposes, an application was written to monitor the CAN bus and capture the data output from
the transmit PDOs. This application displays the information from the PDOs to a
Windows graphical user interface (GUI), and also stores the data to a text file for
offline analysis.

4.2 Respiration and Apnea Detection

To verify the accuracy of the respiration detection system, some tests
were performed with human subjects. In order to perform research on human
subjects at the University of New Hampshire, approval must be granted in
advance by the Institutional Review Board (IRB). Approval for this thesis was
granted, and a copy of the approval letter can be found in Appendix B. The tests
consisted of having the subjects breathe normally while lying on the hospital bed,
while also having a surgical mask with the thermistor taped to the inside placed
over their mouth and nose. The NI USB-6008 and the CANopen application both
logged the respiration data from the measurement instruments to a text file.

The information stored in the text files was imported into MATLAB where
graphs were created to display the measured and control respiration waveforms.
The first test was to determine the accuracy of the measurement system for
detecting the respiration waveform and to determine if the measurement system
accurately identified apneic events. Two subjects were used for this test, one
male and one female. The tests measured the respiration of the subjects over a
few minutes with a period of 10 seconds where the subjects were asked to hold
their breath. The results of the tests can be seen in Figure 4.2 and 4.3.
Figure 4.2 Respiration Waveform of Subject A
The graphs show that the system accurately measured the respiration waveform, and also accurately identified the apneic events. In the measured waveform, the apneic events are identified by the lack of respiration peaks in the waveform and in the control waveform, the apneic events are identified by the lack of voltage fluctuations due to lack of temperature changes. The slope of the control waveform during apneic events is related to the ambient temperature changes the thermistor sensed.
4.3 Bed Movement Verification

While the accuracy of the system's ability to detect respiration rate was essential, the principal objective of the system is to modify a patient's position in the bed when obstructive sleep apnea occurs. This test required the subjects to lie in the hospital bed as if they were sleeping. The researcher instructed the subjects to lie still, as if sleeping, for a short period of about 1 minute. After the minute, the researcher instructed the subjects to hold their breath for 10 seconds. The object dictionary for the system was set up so that Apnea Window was set to 10 seconds. Therefore, if no respiration occurred within the Apnea Window, the application would trigger a bed movement. The results of the test can be seen in Figures 4.4 and 4.5, with a red arrow indicating when the bed movement occurred. The success or failure of the test was determined by visually observing that a bed movement occurred after the subject simulated an apnea.
Figure 4.4 Bed Movement Response of Subject A
Figure 4.5 Bed Movement Response of Subject B
CHAPTER V

CONCLUSION

The primary goal of this thesis was to design and implement a system that would accurately measure a resting subject's respiration waveform, determine when the subject was suffering obstructive sleep apnea, and provide a bed movement as a first response therapy to the apnea all in an unconstrained and noninvasive way. For both subjects that were tested, the system did accurately measure the respiration waveform, and also accurately triggered a bed movement when the subjects held their breath for the length of the Apnea Window defined in the object dictionary.

It was originally intended that the proposed system would be able to measure heartbeat as well as respiration in an unconstrained, noninvasive way. As explained previously, due to limitations of the microprocessor and design choices for other goals of the system, heartbeat was not able to be measured by the final system. However, due to the success of previous research, and the overall success of the final system, it should be possible to expand upon this implementation to include heartbeat detection. Although the final system did not measure heartbeat, obstructive sleep apnea was able to be detected by the system's measured respiration, which was one of the primary goals.
The original bed movement that was intended to be used for treating the apnea's was a patient roll feature that would roll a patient to one side. Sleeping in the lateral position has been shown to decrease the severity and number of apneic events suffered by subjects with obstructive sleep apnea [13], [14]. Unfortunately, this feature of the hospital bed was unable to be accessed by the CAN network. Therefore, an alternate bed movement was used, one that tilted the subjects in the bed, placing them into the trendelenburg position. Despite the inability to utilize the originally intended bed feature, the ultimate goal of automatically controlling the bed's movement based on apneic events was still accomplished.

5.1 Further Improvements

There are improvements that could be made to the overall system. One of these improvements is to modify the amplification circuit to include a variable resistor. One of the factors that influenced the amplification range of the transducer's output was the weight of the subject. In some instances the resistance values in the amplification circuit required adjustments to achieve ideal amplification of the transducer's output to fit the signal into the acceptable range of the microprocessor's ADC. With a variable resistor these modifications could be made more easily and more efficiently.

Another improvement to the overall system would be the addition of a bed position signal. The current system does not provide any mechanism to indicate
that the bed movement occurred. The success of the system, generating a bed movement during an apnea, could be further improved by adding a hardware signal indicating bed movement. Perhaps one voltage level could indicate the bed was at rest, and another voltage level would indicate that the bed was moving. This voltage change could be output to the CANopen network and graphed along with the filtered respiration waveform. The addition of this bed position signal would help prove the success of the system. However, for the purposes of this thesis, the visual observation that a bed movement occurred still proved the success.

Finally, the system could be improved with further development of the GUI. The designed GUI can display information from any of the CANopen nodes, as well as issue CANopen messages to any of the nodes. In its current state, the GUI is only displaying information on the CANopen network. One useful feature would be to include the current Apnea Window value, and allow for modification of this value via button clicks on the GUI. With this feature, a caretaker could make adjustments to the system based on a specific subject's obstructive sleep apnea symptoms.
DEFINITIONS

**Apnea** – Cessation of breathing

**Butterworth filter** – a filter that exhibits the flattest possible response in its passband frequency range

**CANopen** – A communication protocol and device profile specification for embedded systems

**DC component** – the average value of the voltage or current of an electrical circuit over all time

**Embedded Systems** – A specialized computer system which is dedicated to a specific task

**Fast Fourier Transform** – a very efficient computer algorithm designed to calculate the frequency components of sounds and other signals

**Kalman filter** – a filter which estimates the state of a dynamic system from a series of incomplete and noisy measurements

**Lateral position** – Person lying on their side

**Microcontroller** – A processing unit designed to execute small control programs

**Noninvasive** – Any procedure or method that does not penetrate the body

**Phonocardiographic** – An instrument consisting of microphones and recording equipment used to monitor and record heart sounds

**Pneumatic** – Operated by air pressure
**Polygraph** – A device that measures several physiological variables such as blood pressure, pulse, and respiration.

**Prone position** – Person lying on their stomach

**Protocol Stack** – A particular software implementation of a computer networking protocol

**Respirometer** – A device used to measure the rate of respiration of a living organism by measuring its rate of exchange of oxygen and carbon dioxide.

**Supine position** – Person lying on their back

**Thermistor** – A temperature sensor used in measuring respiration

**Unconstrained** – Without any limits or restrictions
REFERENCES


APPENDIX A

PEAK DETECTION ALGORITHM

Below is the MATLAB script used for detecting peaks in the respiration waveform. This script is a modified version of freely available public domain code.

```matlab
% peak detection

mn = 0; mx = 0;
mnpos = 0; mxpos = 0;
lookformax = 1;
delta = 50; % need to adjust this
maxtab = [];
mintab = [];
peak1 = 0;
peak2 = 0;

for i=1:length(sample2)
    % read in current filtered value
    this = sample2(i);
    % if current value is greater than previous max
    if(this > mx)
        % set max value to current value
        mx = this;
        % store position of max value
        mxpos = i;
    end
    % if current value is smaller than previous min
    if(this < mn)
        % set min value to current value
        mn = this;
        % mnpos = i;
    end

end
```
% looking for max means traveling up the waveform
if(lookformax)
    % if current value is less than previous max minus delta (new peak)
    if(this < mx-delta)
        maxtab = [maxtab ; mxpos mx];
        % copy old peak
        peak2 = peak1;
        % new peak is found at position mxpos with value mx
        peak1 = [mxpos mx];
        % set minimum value to current value (going down the waveform)
        mn = this;
        mnpos = i;
        % not looking for max right now
        lookformax = 0;
    end
    % traveling down the waveform
else
    % if current value is great than previous min plus some delta (new min)
    if(this > mn+delta)
        mintab = [mintab ; mnpos mn];
        % set maximum value to current value (going up the waveform)
        mx = this;
        mxpos = i;
        % start looking for a peak again
        lookformax = 1;
    end
end
end
APPENDIX B

IRB APPROVAL LETTER

University of New Hampshire
Research Integrity Services, Office of Sponsored Research
Service Building, 51 College Road, Durham, NH 03824-3585
Fax: 603-862-3564

25-Mar-2009

Waters, Jonathan
Electrical & Computer Engineering, Kingsbury Hall
25 7 Springs Ln Apt 105
Burlington, MA 01803-5150

IRB #: 4253
Study: Measurement of Physiological Factors While Resting
Review Level: Expedited
Approval Expiration Date: 27-Mar-2010

The Institutional Review Board for the Protection of Human Subjects in Research (IRB) has reviewed and approved your request for time extension for this study. Approval for this study expires on the date indicated above. At the end of the approval period you will be asked to submit a report with regard to the involvement of human subjects. If your study is still active, you may apply for extension of IRB approval through this office.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the document, Responsibilities of Directors of Research Studies Involving Human Subjects. This document is available at http://www.unh.edu/osr/compliance/irb.html or from me.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,

[Signature]
Julie F. Simpson
Manager