Ventilation Monitor
Final Design Report

May 5, 2008

Padraic Casserly
Andrew Dias
Joey Labuz
Joel Webb

Advisor and client: Professor John G. Webster

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Abstract

Ventilation monitors can save lives of firefighters on the job by alerting rescue personnel if breathing stops. These monitors exist but are very expensive - up to $8,000 each. Our goal was to build our own ventilation monitor in a much more cost-effective manner. The most popular method to measure ventilation is inductance plethysmography because it is noninvasive. We built our own monitoring chest strap. The strap we built is connected to a circuit which gives a frequency output proportional to the cross sectional area of the chest. Typical outputs range from 750 to 900 kHz depending on the size of the chest. A frequency to voltage converter gives a voltage output that can be amplified and wirelessly transmitted. We observed a voltage change of 10 mV for a change in 10 kHz in our oscillator output when testing the converter with a signal generator.

Background Information

As the ventilation team, our goal is to design a device that will measure the respiration rate of the firefighter wearing it. Our device will send a wireless signal to a command center. At this command center, personnel will be able to monitor the breathing rate of the firefighter wearing our device.

The need for this device is to increase firefighter safety. In an emergency situation, firefighters are exposed to many dangers such as smoke. Although most firefighters wear numerous protective devices to prevent the inhalation of these toxins, 123 deaths have occurred due to asphyxiation in the last ten years (U.S. Fire Administration, 2007).

Year	Deaths
2006	12
2005	8

2004	5
2003	6
2002	15
2001	18
2000	13
1999	16
1998	15
1997	15

Table 1: U.S. firefighter deaths by asphyxiation per year (U.S. Fire Administration, 2007).

The overall goal of the ventilation monitor is to alert rescue personnel if a firefighter's breathing rate reaches dangerous levels. If this were the case, the firefighter could be rescued and given medical attention before the situation becomes fatal.

Some devices measuring ventilation exist today. These devices use a variety of designs and technologies. The most popular technology used is inductance plethysmography. This technique is noninvasive and is used to measure a change in lung volume. Most inductive plethysomgraphs are built using a chest strap. This strap is embedded with a circuit fashioned in a way that stretching of the strap changes the inductance. The strap around the chest acts as a circuit loop. As the person wearing this strap breathes in and out the chest expands and contracts. This expanding and contracting of the chest changes the cross-sectional area of the loop. Magnetic flux is a function of the area of a loop according to the equation:

$$\Phi_m = \iint \mathbf{B} \cdot d\mathbf{S}$$

Magnetic flux (Φ [W]), magnetic field (B [T]), and surface area (S [m^2]) (Serway and Jewett, 2004)

$$L = \frac{\Phi}{i}.$$

Inductance (*L*), magnetic flux (*Φ*), and current (*i*) (Serway and Jewett, 2004)

Breathing changes this cross sectional area by expanding a chest strap and thus changes the flux, which changes the inductance of the circuit. Through the use of different circuit elements, inductance plethysmography turns this inductance into a voltage. This voltage can be wirelessly transmitted.

Design Specifications

According to criteria established in meeting with our client and through literature research, our device must fulfill several requirements. The device must be able to detect expansion and contraction of the chest and wirelessly transmit that data to a nearby command post. The inductance band itself must be able to fit most firefighters comfortably meaning that it must not slip as the firefighter wears it, nor cause itching, irritation, or rashes. It must also be less than 0.5 kilograms so as not to interfere with the firefighter's range of motion. Since the device will be worn next to the skin, it must be able to accommodate temperatures near 40 °C and withstand moderate amounts of moisture due to sweat.

The device will be used frequently, so the fabric and wire must be resistant to wear and cannot rip. The belt itself should be easy to clean and sterilize. Ideally it will be washable. We expect the device, with proper maintenance and periodic replacement of the power source, to have a life in service of at least five years.

Current Products

There are currently several devices that are designed to monitor firefighter ventilation on the market today, but they are quite expensive. Our aim is to create a simplified device that does not have all the extra functions of current products, but as a result is much cheaper.

Figure 1: The monitoring belt for the VivoMetrics® VivoResponder^{TM} (VivoMetrics, Inc. 2007)

One well-established device is the VivoMetrics® VivoResponder^{TM} system (Figure 1). It is similar to our proposed device in that it measures respiration using an inductance plethysmography chest band. The band is lightweight (100 g) and comfortable. Data is wirelessly transmitted to a command center, as we plan to do. The cost of the device – $2500 to $8000 for a single unit – is much more than our target price.

The VivoMetrics® VivoResponder^{TM} is so expensive because it offers many features. In addition to rate of respiration (what we plan to measure), it also monitors heart rate, skin temperature, activity, and posture (VivoMetics, Inc., 2007). It is easy enough to measure skin temperature and heart rate, but posture and activity would be slightly more complicated. We believe that by limiting ourselves to monitoring breathing rate, we will be able to provide a device at a fraction of the price.

A second device currently available today is the MSA TxR ICM® Accountability System (Figure 2). Rather than a strap-based system, this device is meant to be integrated with a self-contained breathing apparatus (SCBA). It monitors temperature and has an accelerometer to monitor how/if the firefighter is moving. It also monitors breathing rate and the amount of air left in the SCBA system. From these data, it is able to calculate how much longer a given SCBA tank will last. The device also has a two-way communication system that allows the command center to issue an "evacuate" command. The firefighter can confirm reception as well as initiate a distress signal.

Figure 2 - The MSA TxR ICM® Accountability System. The unit with the computer is the sensor and also serves as a miniature display.
(MSA, Inc,. 2006)

This device is slightly cheaper than the VivoMetrics® VivoResponder^{TM}. It starts at $1800 per unit (MSA Inc., 2006). Again, we hope to keep our device affordable by eliminating the use of such expensive sensors.

Inductance plethysmography straps are also available commercially. Again, they are too expensive for our purposes so we will design and build our own strap. The first strap we looked at was the MVAP Respiratory Inductive Plethysmography (RIP) belt (Figure 3). According to the company catalog, the belts start at $260.

Figure 3: MVAP RIP belt (MVAP Medical Supplies, Inc. 2006)

Another company that sells inductance

plethysmography belts is Ambulatory Monitoring Inc. A band for a regular adult (28” to 36” chest circumference) costs $70 (Ambulatory Monitoring, Inc., 2005)

Chest Strap Design

Our chest strap will be based on an old belt used by the UW Sleep Apnea Lab. It will be made of cotton knit fabric which costs $2.50 per square yard. Cotton knit will work well because it is lightweight, flexible, and breathable. The belt will be fastened by Velcro, and two wire leads will connect the belt to the rest of the circuit. The belt will be designed to fit chests from 75 cm to 125 cm in circumference. Wire will be woven through the fabric in a zigzag pattern (Figure 4). This belt will be used in designs one and two, and a modified version will be used in design three. The modified version does not include a wire running around the chest strap but will instead package all components on one side of the belt.

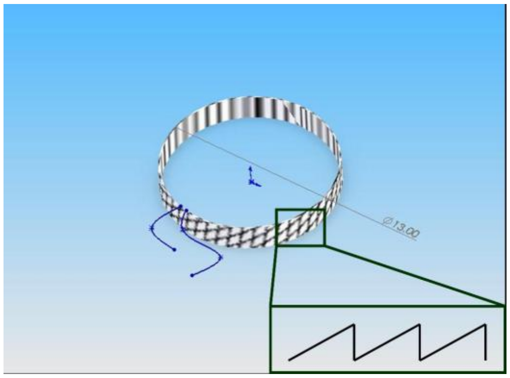

Figure 4: Chest strap design. Wire will be woven through the knit cotton fabric in a zigzag pattern as shown in inset. Two leads will connect the strap to the rest of the circuit. Circumference ranges from 75 to 125 cm

Design 1: Inductance plethysmographer featuring Colpitt’s Oscillator

Our final design consists of a Colpitts oscillator in which the inductor has been replaced by a chest strap of variable inductance (L Band in Figure 5). The output of the oscillator is then filtered and amplified before being fed into a frequency to voltage converter chip. The output of the chip theoretically yields a voltage that varies linearly with inductance (Analog Devices, 2006). This voltage can then be transmitted and processed as desired.

We chose the following Colpitts oscillator circuit to yield a frequency output between 800 and 900 kHz depending on the inductance of the band:

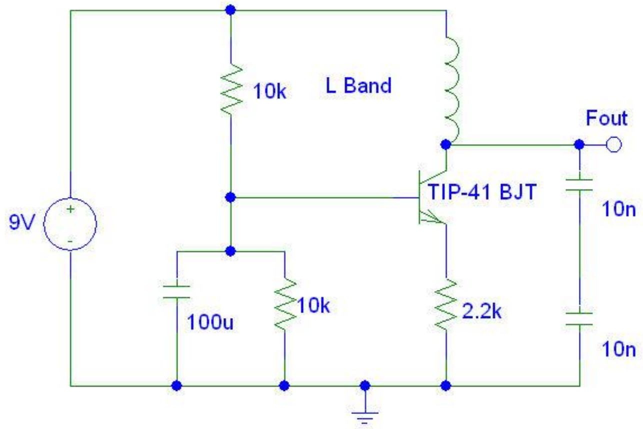

Figure 5: Colpitt's oscillator circuit with component values (Wikipedia.org, 2008).

The frequency of this oscillator can be represented by the equation:

$$f_0 = [L_{band} * 10n * 10n /(10n + 10n)]^{-1/2} / 2\pi$$ (Cohen *et al*, 2004)

Frequency of the oscillator at the bipolar junction transistor is thus proportional to $L_{\mathrm{band}}^{-1/2}$, but for small changes in chest strap inductance, we can treat the frequency change as linear and approximate it by a Taylor polynomial (Cohen *et al*, 2004). The amplitude of oscillations drive an emitter and an isolated circuit will then generate an output voltage that can be sent to a command center. Cohen *et al* describe a number of assumptions about connectors to the circuit. Coaxial cables and other wires should not have inductance, and if there is any it is assumed to be substantially smaller than that of the inductor.

Finally, the signal will enter a frequency-to-voltage converter chip ($15, Analog Devices) and its support circuitry. The various capacitor and inductor values were determined using equations supplied to us by the manufacturer.

$$C_{os} = \frac{t_{OS} - 3 \times 10^{-7} sec}{6.8 \times 10^{3} sec/F} \qquad C_{INT} = \frac{Mechanical\ Response\ Time}{N \times R_{INT}}$$

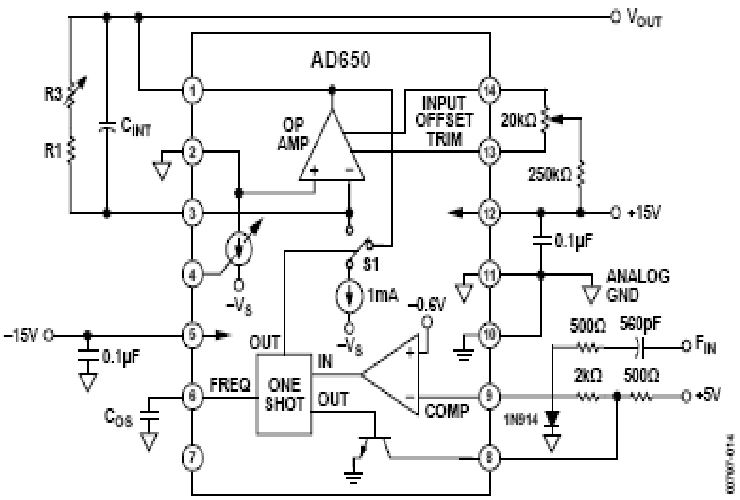

Figure 6: Equations used to calculate certain component values. Schematic of frequency to voltage converter using the AD650 chip. C_{int} = *1 µF,* $R_1 + R_3$ = *160 kΩ,,* C_{OS} = *80 pF. We chose* t_{os} *to be* 9×10^{-7} *seconds.*

Design 2: Inductance Plethysmography featuring a Low-Pass Filter

Our second design also uses the principle of inductance plethysmography to monitor breathing rate noninvasively. Again, a wire is sewed into a chest strap, and when a current runs through this wire there is self-inductance in the band. In this design, the inductance band is an element in a low-pass filter:

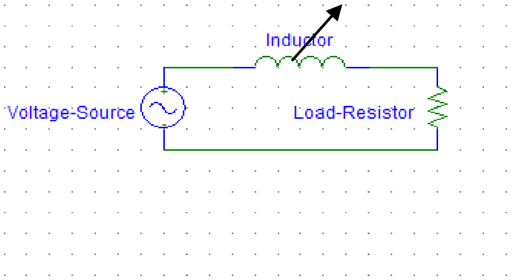

Figure 7: A low-pass filter with the chest strap band as the inductor. Inductance is variable and is based on the chest strap. The voltage source and resistor values are not specified because we do not yet know what sort of values to expect for the inductor. These values will be determined after testing.

The corner frequency f_c of this circuit is variable as $R/(2\pi L)$ (Figure 8), but the frequency of the voltage source is always constant.

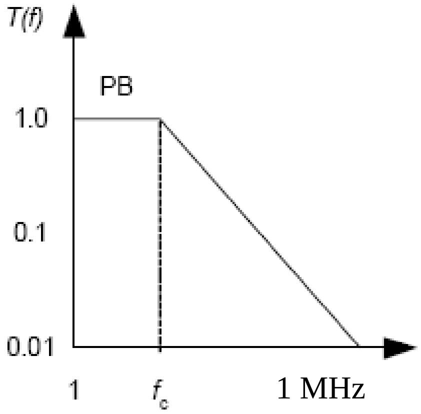

Figure 8: The frequency response of a low-pass filter. When frequency goes above the corner frequency f_c, the voltage input is attenuated and the output is very low. (Webster, 2004)

As the inductance of the chest strap varies, the corner frequency is proportional to L^{-1}. As inductance increases with cross sectional area of the chest strap, the corner frequency will shift left. The voltage source frequency should be set to the maximum corner frequency – when the chest strap is completely contracted. When the corner frequency shifts left, the voltage of the source will be attenuated and there will be a lower output voltage. The output voltage would be amplified and transmitted to give a ventilation reading.

The value for the resistor was not chosen because the chest strap inductance needs to be determined. The inductance needs to be determined by testing because there will only be one loop around the chest and the resulting inductance change will be very small. The voltage source will be relatively small (less than 5 V), and its value was not chosen yet because we do not know how much the corner frequency will vary. If there is too small of a change in corner frequency, then the attenuation of the filter will not be large. If a differential amplifier is used, the input difference (V_{source} - V_R) will be too small to yield a large enough output voltage. If we cannot get a large enough frequency shift, then the voltage source would need to have a higher voltage in order to provide a large enough input difference for the amplifier.

This design is desirable because of its simplicity, but there are a few problems that render it ineffective. First, there can be baseline shifts, and because we are operating based on a very small change of inductance, the baseline could very easily go off the scale and saturate our output device. Also because of the small change in inductance, using a comparator or differential amplifier would be difficult. The change in voltage may be too small to measure. However, a trim potentiometer might mitigate this problem. Second, as the corner frequency approaches the frequency of the source, the phase of the inductor falls from 90° to 45°. As a result, we may not be able to amplify our output voltages.

Design 3: Linear Variable Differential Transformer (LVDT)

Our third design is a linear variable differential transformer (LVDT). It is unlike the other two designs because it does not use inductance plethysmography. As the chest of the firefighter expands and contracts while breathing, a ferrous rod slides inside of a tube through three sets of coils. An alternating current is driven through the primary coil as seen on the left in Figure 9. This causes a voltage to be induced in each of the secondary coils proportional to that of the primary. As the core moves through the system, these mutual inductances change,

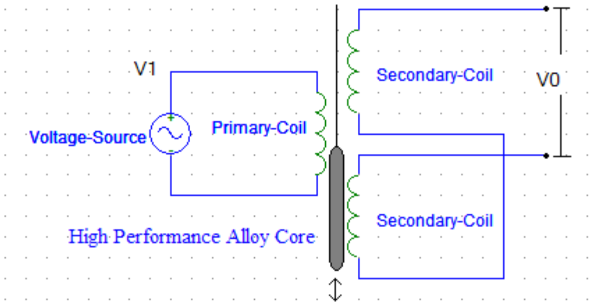

Figure 9: A diagram of an linear variable differential transformer.

causing the voltage induced in the secondaries to change. This change in voltage can be transmitted to the command center.

This design has two positive aspects. First, it has proven to be extremely accurate and easy to measure because the change in voltage in voltage is large. The circuitry is not complex and the output of the sensor is a voltage, so the conversion of an inuductance to a voltage is not required. Unfortunately, it is quite expensive. According to manufacturers' websites the LVDT unit can cost between $115 and $800 (Omega, 2007).

Design Matrix

The LVDT scored so poorly on the design matirx (Table 2) in the cost category precisely because of its high cost. The other two designs are composed of cheap circuit components, which is why they scored higher. Cost was an important consideration for us because our goal is not to create new technology but compete against existing ones.

	Weight	**Colpitts Oscillator**	**Low-pass Filter**	**LVDT**
Safety	20	**18**	18	15
Signal Strength	25	**17**	10	22
Comfort	15	**13**	13	8
Cost	20	**15**	19	4
Manufacturability/feasibility	20	**16**	12	18
Total	100	**79**	72	67

Table 2: Design Matrix. Based on this evaluation, we chose the Colpitts Oscillator as our final design with a total score of 79 out of 100 points.

Our highest weighted category was signal strength. The LVDT design scored the highest in this category because unlike the other two designs which use inductance plethysmography and give very small voltage differences, an LVDT gives a large voltage output. Thus, the voltage is easily amplified before it is transmitted to the command center.

Safety is an important category simply because this device is to be worn by people whose main priority is safety. The firefighters who ultimately wear the final product should not have to be worried about the safety of their equipment in high-stress situations. LVDT scored lowest in this category because it requires a higher voltage.

Manufacturability/feasibility was the last category of large importance. We want this device to be scaled to mass production and readily available circuitry is not difficult to manufacture. The LVDT is readily available and easily manufacturable. The low-pass filter scored low because, as to date, there have been no advancements in solving the problem of base-line shifts. Thus, the low-pass filter may be manufacturable but is not feasible. Ultimately, Design 1, the Colpitt's Oscillator was chosen to be the final design based on the design matrix.

Prototype and Testing

The strap we constructed is made of a poly-cotton blend that is lightweight, stretchable, and breathable. Stranded wire – which is more flexible and less brittle than regular wire – is woven through in a zigzag pattern and the strap is fastened with Velcro. The strap is very thin, 15 cm (6 in) in height, and about 32 cm (13 in) in diameter. It fits chest sizes from about 75 to 90 cm in circumference. In order to ensure comfort, excess fabric is folded over so that no wire and very few stitches come in contact with the skin of the wearer.

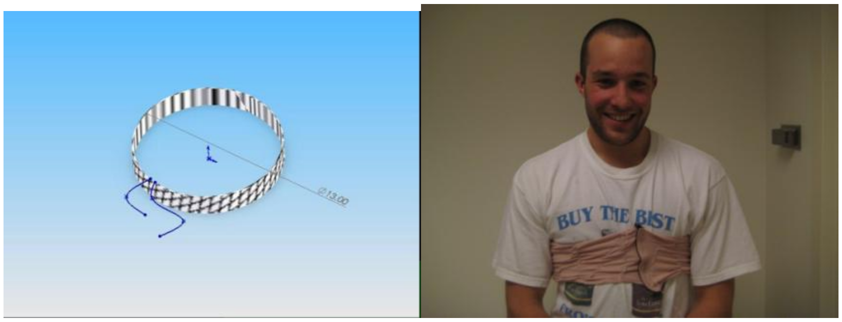

Figure 10: (Left) Solidworks rendition of the chest strap, (Right) a team member wearing the inductance band.

In figure X, L Band represents the chest strap of variable inductance. Although some commercial straps start at $260 (MVAP Medical Supplies, Inc. 2006), we were able to build our own strap for under $5.

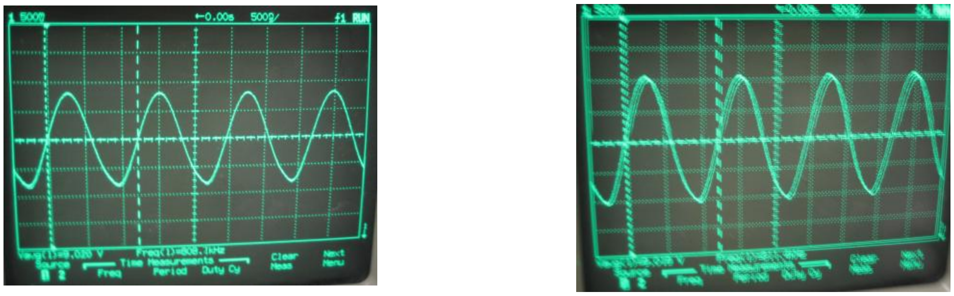

Figure 11: Pictures of the oscilloscope readings during exhalation (left, approximately 808 kHz) and inhalation (right, approximately 814 kHz).

The oscillator we built yielded a frequency change of about 6 kHz when the strap was used as L Band when a subject inhaled and exhaled (Figure 11). The amplitude of this signal is 0.8 V peak-to-peak.

By experimentation with a signal generator, we found that the frequency-to-voltage converter circuit required a peak-to-peak voltage of at least 2.4 V. Because the oscillator circuit only had an output of 0.8 V peak-to-peak, a filter and amplifier circuit were built. In order to discard the DC offset, a high pass filter with a corner frequency of 1.6 Hz (C = 0.1 μF and R = 1 MΩ) was used. Next, a non inverting amplifier with a gain of 4 (R_f = 3 kΩ and R_i = 1 kΩ) was used. The team succeeded in attenuating the DC component of the signal but was unable to then amplify the AC component. We expected a gain of 4 but observed a gain of 0.3.

Conclusion and Future Work

We have demonstrated that using a chest strap to measure ventilation produces a measurable change in frequency of an oscillator. Separately, we have demonstrated that a change of 10 kHz of a signal at the frequency of our oscillator yields a voltage change of 10 mV at the output of our frequency to voltage converter. The only remaining component of the project is to amplify the signal from our oscillator. We were unsuccessful with this amplification for reasons we do not understand

There are no ethical considerations to speak of when testing our device. The monitor was designed to be noninvasive and voltages are low enough that testing on a human should not be harmful at all.

The way our prototype stands, we have been unable to obtain a voltage output based on expansion and contraction of the wearer's chest. By testing our frequency to voltage converter with a signal generator, we found that the converter requires a signal with AC amplitude of 2.4 volts. Our oscillator has an output signal with AC amplitude of about 0.8 volts. We have filtered out the DC component of our signal and attempted to amplify the resulting AC current using a noninverting amplifier. Attempts so far have been unsuccessful for reasons we do not understand. However, all that remains to be done to obtain a voltage signal that corresponds to ventilation is to amplify our oscillator signal.

Once a voltage signal is obtained, future groups can focus on other design criteria necessary for a mass-producible product. The final product should be portable and fit on the chest strap itself. It must include a wireless transmission circuit component that transmits the voltage signal to a command center that could store the data. A program could be written that will process the data and graph it as a function of time. Finally, testing could be done to ensure usability of the device with people of different chest sizes, determine battery and circuit life, and test for the maximum radius of wireless transmission.

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Appendix 1: Product Design Specification

Ventilation Monitor

Padraic Casserly, Andrew Dias, Joey Labuz, Joel Webb
Client and Advisor: John Webster, PhD
Last Updated: 5/4/08

Function

We intend to develop a wearable, expandable chest strap to measure and transmit ventilation data to a central command center. This device will be especially useful to monitor the vital signs of firefighters and other first responders in hazardous situations. We hope to deliver a more inexpensive product than current models on the market.

Client Requirements

- Fits under clothing
- Measures respiration
- Real time remote data
- Light, durable material
- Comfortable
- Transmits data

Design Requirements

1. **Physical and Operational Characteristics**
    a. Performance requirements – withstand daily use, easy to put on

    b. Safety – No exposed wires, no risk of shock/short circuit, no interference with other devices.

    c. Accuracy and Reliability - Should send a signal indicating whether the firefighter is breathing or not.

    d. Life in Service – 5 years

    e. Shelf Life – 5 years

    f. Operating Environment – Must tolerate moisture, temperatures up to 40 °C, repeated stretching.

    g. Ergonomics – No slip, minimal rotation, male vs. female form

    h. Size – Variable girth, less than 1 cm thick, width 15 cm

  i. Weight – not more than 0.5 kg

  j. Materials – knit cotton fabric, Velcro, basic circuit elements.

  k. Aesthetics, Appearance, and Finish – texture should be smooth so as not to irritate skin.

2. **Production Characteristics**

   a. Quantity of units needed – 1 prototype, but a mass producible design

   b. Target Product Cost – $100

3. **Miscellaneous**

   a. Standards and Specifications – N/A

   b. Customer – NONE

   c. Patient Concerns – washable, non-allergenic

   d. Competition – Vivometric VivoResponder (pat #468-6999), PASS (no signal, alarm), Fireeye Heads-up display, Sensetech interwoven fabric, MSA ICM TxR Accountability System, Ambulatory Monitoring chest strap