ACOUSTIC SENSOR FOR HEALTH STATUS MONITORING

by

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ABSTRACT:

ARL is developing sensor technology to monitor soldier's health and activity by gathering and analyzing acoustic data. The sensor consists of a fluid or gel contained within a small conformable rubber bladder or pad that also includes a hydrophone. This enables the collection of high signal-to-noise ratio heartbeat, breath, voice, and other physiology. The pad also minimizes interference from ambient noise due to its poor coupling with airborne noise.

When the sensor pad is in contact with a patient's thorax, neck, or temple region, sounds can be immediately and continuously monitored. This can aid in the assessment, diagnosis, and treatment of cardiac and respiratory functions, as well as provide human stress and performance indicators such as heart and breath rates, voice stress, and gross motion indicators. A medic can safely interrogate fallen soldiers for remote casualty-care triage or assess the condition of those missing in action.

Data were collected on soldiers during normal training activities. Acoustic monitoring pads were placed on the soldier's chest, neck, and helmet headbands to gather their body's acoustic signatures, and a calibrated air microphone was placed closely to the front of their mouth's to document breathing, voice, and ambient noise. An accelerometer was used to document footfalls, and the output of a bipolar electrode heart rate monitor was simultaneously recorded to provide heartbeat timing information to help discriminate between heartbeats, breaths, footfalls, and other activity. Waveform and spectrogram representations of the data will be presented, and conclusions will be drawn.

Unlike most medical sensor technologies, which look at only one physiological variable, a *single acoustic sensor* can collect information related to the function of the heart, lungs, and digestive tract or it can detect changes in voice or sleep patterns, activity, and mobility. It can also provide situational awareness clues as to how the soldier is interacting with the battlefield and the mission.

1.0 BACKGROUND:

ARL developed a new method to measure human physiological stress parameters. This was accomplished with the use of an acoustic sensor positioned inside a fluid-filled bladder in contact with the human body. With the sensor packaged in this manner, the outside environmental interferences are minimized, and signals within the body are transmitted to the bladder with minimal losses. This fluid coupling allows comfortable and conformal contact to the human body, and enhances the SNR of human physiology to that of ambient noise. This sensor is not readily available, because the development has not been completed. An acoustic sensor of this type could be a tremendous asset in determining soldier stress levels during performance type tasks.

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ARL is developing sensor technology to monitor soldier?s health and activity by gathering and analyzing acoustic data. The sensor consists of a fluid or gel contained within a small conformable rubber bladder or pad that also includes a hydrophone. This enables the collection of high signal-to-noise ratio heartbeat, breath, voice, and other physiology. The pad also minimizes interference from ambient noise due to its poor coupling with airborne noise.

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2.0 SIGNIFICANCE:

An acoustic sensor system can detect changes in the person's health status resulting from exertion or injuries such as a trauma, penetrating wound, hypothermia, dehydration, heat stress, and many other illnesses or occurrences. Upon indication of a dangerous condition, corrective procedures can be recommended, or alerts to medical personnel or supervisors can be initiated. Managers can use preparedness and health data as a decisional aid for manpower allocations. Training participants can be cognizant of performance levels achieved or dangerous health indicators present. The physiological data collected during training or routine tasks can be useful for predictive modeling and simulation of worker performance in a virtual workplace, especially in the development of new operative environments or procedures.

Acoustic sensors can be useful for determining worker stress level, fatigue, or attention deficits that may help reduce the occurrences of injuries in the workplace. External factors, such as smoking or allergies, can be additional clues to help interpret changes in acoustically detected physiology. Baseline screening and continued surveillance of worker respiratory condition can be valuable for health history understanding. Acoustic sensors and signal processing may allow the prediction of injury or unsafe actions, based on advance knowledge of health and performance trends resulting from the interactions between a soldier and his mission or a worker's job performance, his limitations, the machines, and workplace environment.

Changes in methods and techniques will be quantifiable using acoustic techniques to relate the person's physiology with his or her environment or tasks at hand. Baseline physiology documented during a normal task can be compared to physiology resulting from a "new and improved" method or piece of hardware. What was normally quantified with a stopwatch and questionnaire can now be enhanced with "holistic" data that evaluates so much more than the speed or cost of the new approach.

A sensor contacting the torso, head, or throat region picks up the wearer's voice very well through the flesh. Since the monitoring pad's bandwidth permits intelligible voice, the speech data collected through the wearer's body can be useful for voice-stress analysis. By sensing the voice through the body, a higher SNR can be obtained in noisy environments. This sensor can also be used as a hands-free method to activate machinery, shut down equipment, enable a communication transmitter, activate a heads-up display, or even tag menu functions on a computer. An auxiliary air-coupled sensor may be used to quantify the acoustic ambient to relate ambient noise to stress and auditory health.

Civilian technology transfer applications include SIDS, apnea, and infant monitoring as well as clinical surveillance in convalescent and V.A. homes, medical transports, hospitals, and telemedicine applications [Scanlon, US Patents]. Drivers of vehicles and aircraft could also be monitored for the onset of sleep, seizure, or heart attack.

3.0 ACOUSTIC DIAGNOSTICS:

There is physiological significance to how the timing of heart beats changes from beat to beat, known as the inter-beat-interval (IBI) or heart rate variability. Heart rate variability (HRV) is a measure of mental workload, and HRV decreases as a function of effort invested in a task. FFT analysis of the heartrate variability can be decomposed into three different control mechanisms: the low, medium, and high frequency bands respectively relate to body temperature regulation, short-term arterial pressure regulation, and respiratory activity [Mulder and Mulder]. A measurement such as IBI can be taken at the wrist, neck, temple, or chest. Changes in valve timing may also provide clues on cardiology and overall physiology. However, valve sounds are primarily available at the chest area with some components discernable in the neck region.

Fourier analysis of the monitoring pad's output has already shown that human cardiopulmonary function contains infrasonic (sounds below 20 Hz) signals, which cannot be heard with human ears, but may be useful for physiological monitoring and medical diagnostics. Spectral details of individual valve and chamber activity can be monitored for timing and quality as well. For example, the first heart sound is a result of the mitral and tricuspid valves closing. Whereas the second heart sound results from the aortic and pulmonic valves closing. When breathing in, the interval between the aortic and pulmonary valve closures increase, and allows both sounds to be heard independently. By monitoring the amplitudes of the first heartsounds, which are correlated to the left ventricle pressures, cardiac contractility can be measured [Hansen, Luisada, Miltich, Albrect]. Systolic blood pressure values from and individual patient can be approximated from sound-pattern analysis of the second heart sound. When correlated with a known systolic measurement, sufficient precision exists [Bartels, D. Harder].

Various statistical measures of breathing cycles can be linked to different aspects of central respiratory control, such as the ratio of tidal volume to inspiratory time (reflects strength of inspiration) and the ratio of inspiratory time to total duration of the breathing cycle (reflects breathing periodicity). "Minute" ventilation is the product of tidal volume and respiratory rate, and is a common analysis parameter [Milic-Emili, Grassino and Whitelaw]. The acoustic amplitude of the breaths can be related to volumetric flow [Kramn], which, when combined with breath rate, can be a very useful monitoring parameter.

Muscle sounds, such as the Piper-band sound created in the wrist during flexion and extension of the wrist is in the 40-50 Hz region for healthy adults. But the Piper-band sound changes to pulsatile muscle activity of 10 Hz for patients suffering from Parkinson's disease. This suggests that auscultation of muscle activity can be of diagnostic value, and that changes in acoustic content may indicate transition to suboptimal muscle function when fatigue or injury occur [Brown].

Monitoring of joint sounds resulting from repetitive motions, such as squatting, reaching, or twisting, can be useful for determining degradation of joint tendons, ligaments, and cartilage [Prinz and Ng], [Brodeur]. This could be useful data when implementing new hardware, reorganizing a workstation or redefining tasks, as well as for monitoring long-term repetitive stress injury effects or recovery from existing conditions. The elimination of joint-sound occurrence improves personal safety, comfort, and long-term health and performance.

4.0 ADVANTAGE OF ACOUSTICS:

Cardiovascular activity can be the result of many factors: cognitive activity, respiration, exercise, temperature, chemical, emotional, and physiological. By monitoring heartrate only, it is very difficult to interpret the resulting physiology, and to determine the contributing factors. More physiological indicators quantified can result in better understanding of the entire picture. Human acoustic sensing provides a low-cost, lightweight, and adaptable means of monitoring many aspects of human or animal physiology, as well as his interaction with the environment that may be influencing his performance. A *single* acoustic sensor can collect information relating to the functionality of the heart, lungs, gastrointestinal tract, or detect changes to patterns in voice, activity, sleep, and mobility. The software algorithms to evaluate data from acoustic sensors can be continuously modified to monitor new parameters, the correlation between dissimilar body functions, other medical sensing technologies, or even the interrelations between the worker's physiology, the task at hand, and the surrounding area.

5.0 BENEFITS OF SUCCESSFUL COMPLETION:

The ability to continuously monitor a soldier's performance level before, during, and after combat missions provides military leaders a decision aid for increased mission effectiveness. Heartbeats, breaths, motion, and other physiological sounds relating to injured and uninjured soldiers can be detected, transmitted, and analyzed for diagnostic purposes [Scanlon]. In the future, neural net classifiers could diagnose medical condition based on combined sensor technologies. Such advancement in the state of the art of physiological sensing can have a huge impact on the entire medical monitoring and research communities, as well as human performance monitoring.

6.0 SENSOR PLACEMENT:

Sensor mounting hardware, such as straps and chest harnesses were developed. The intent of the mounting mechanisms was to maintain the implementational flexibility necessary to mount the sensors in several different locations on the human body. However, it is recognized that an optimized configuration for one particular body location may not work as well on other areas of the body. There are significant trade-offs to be considered for placement of the sensor on different body locations. One of these is user acceptance. If the user (test subject) does not like the attachment location, sensor placement or attachment method is uncomfortable, or if either interferes with his normal activity or abilities, it will adversely effect the test/mission and will not be useful.

Of significant importance is the availability of an acoustic signature present at that location which relates to a physiological parameter or indication. Obviously, the further the sensor is placed from the heart, the less sound will be detected. This also is a SNR issue, in that other physiology, motion, or external noise may mask the signal of interest. An example of this might be the loss of relatively quiet breath sound data detectable by a chest sensor during very intense physical lifting or motion that uses chest and arm muscles.

Quality of the data is an important decision to be made. Is the purpose of the monitoring sensor to detect the occurrence of a heartbeat or subtle characteristics of the heartbeat? Spectral details of heart valve activity or lung sound quality may be an indicator of cardiovascular performance and health, yet heart-rate and breath-rate may be an indicator of exertion or activity. There is also physiological significance to how the timing of heart beats changes from beat to beat, known as the inter-beat-interval (IBI) or heart rate variability [Mulder and Mulder]. A measurement such as IBI can be take at the wrist, neck, temple, or chest, but valve sounds are primarily available at the chest area with some components discernable in the neck region. Monitoring the wrist area can provide heart rate and movement indicators, but may also give breath indications since the amplitudes of first and second heart sounds were found to increase during expiration [Ishikawa, Tamura].

Several different sensor configurations developed for evaluation include: torso mounted, neck attachment, standard PASGT helmet headband mount. An arm attachment can also be used on the wrist or leg to detect pulsations of the extremity's artery. The headband attachment detects the temple pulse, breath sounds through the sinus cavities and tissue, as well as speech through bone and tissue conduction. This sensor could also be attached to a helmet headband, hat or gas mask. The neck attachment collects excellent speech and breath sounds. The pulse is also detectable from the carotid artery. This attachment area is often unobstructed by other equipment or clothing, and is easy to attach quickly to a test subject who may be beginning a test.

An adaptable chest harness was designed to allow flexible placement of the sensor at various points on the torso front, back, and sides. This may be necessary during tests to determine where certain physiological sounds are loudest, or where to place a sensor so as not to interfere with other equipment or hardware. A simplified chest attachment hangs from the neck by a simple band. The placement of the sensor falls just above the sternum, very near the aortic valve for good heart sounds as well as breath sounds. Voice detected at this location is somewhat intelligible, but higher-frequency components resulting from the vocal cords and mouth/sinus influence are not heard, limiting understanding.

7.0 SENSING ELEMENT:

I configured a thin-disk flexural piezoelectric element within a fluid chamber for preliminary coupling measurements. This gave me signal and noise levels, and a basis for circuit development. Preliminary data analysis indicated the flexural-disk hydrophone might provide useful bandwidth to the 2500 Hz goal. Experimentation led to the selection of a thin, flexural disk, piezoceramic element that improved sensor bandwidth and sensitivity over earlier devices. Additionally, the exposed surface of the new, low-cost, sensing element is resistant to corrosion or failures due to continuous submersion in liquid. Other sensor materials such as piezoelectric rubber (PZR), 1,3 piezocomposites, PZT, electret, etc. were gathered and evaluated, but considered inappropriate from the implementation point of view or not meeting sensitivity and bandwidth goals. The piezoelectric material that is deposited on the flexible metal membrane is somewhat brittle, and care should be taken not to push directly on the sensor face, since micro-cracks resulting from overstressing the diaphragm may cause decreased sensitivity. Other materials such as PVDF, a flexible piezo-electric material, would be more durable, and conform better to the contours of the human body. This and other materials and sensors are still being evaluated.

8.0 SENSOR DESIGN:

A sensor prototype, consisting of sensor, housing, fluid-cavity, preamplification, and filtering circuitry was designed and fabricated, and is shown below in figure 1. Sensor cross-section and assembly drawings are shown in figures 2 and 3.

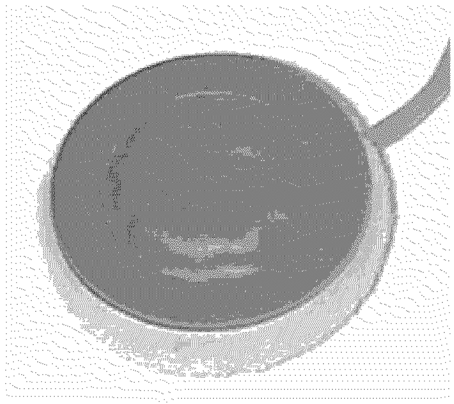

Figure 1: Acoustic Sensor.

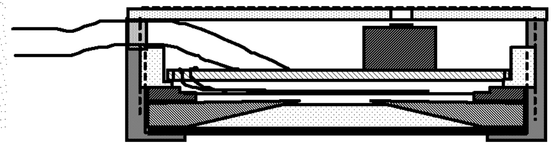

Figure 2: Sensor cross-section.

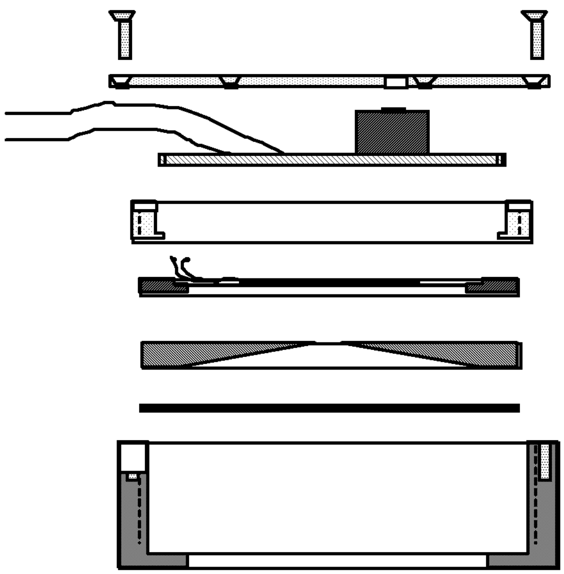

Figure 3: Sensor assembly drawing.

A conical focusing aperture was implemented to provide aperture gain, and direct the acoustic energy to the most sensitive area of the sensing element. The sensor housing allowed reconfiguration with new components, diaphragm, fluid, or sensing element. The fluid and rubber combination provide acoustic impedance matching, much like high performance clinical and industrial ultrasonic transducers require a matching layer with controlled acoustic properties. Other materials such as polyvinyl alcohol gel exhibit similar acoustic properties to that of human flesh, and minimal sound transmission losses [Hayakawa, Takeda, Kawabe, and Shimura]. Aqueous ultrasonic coupling gels, perfected for ultrasonic imaging, were the first fluids to be evaluated within the sensor cavity. However, the high viscosity and typical presence of trapped air bubbles made it difficult to reliably implement. Any suspended air bubbles within the interface cavity will act as compliance and attenuate the acoustic physiological signals. The majority of testing was conducted using water as the coupling fluid, with nearly similar acoustic sound-speed and density to that of human flesh. The sensor was attached to various locations on the human body to assess acoustic emissions and determine if interfering acoustic signals are present. Considerable physiological data was collected and analyzed using time-frequency analysis techniques developed using LabView software. Correlation between airflow and throat sounds was verified by experimentation. Acoustic heart-rate determination was verified by Propaq and Polar brand heart-rate monitors; both accepted within the medical community.

9.0 TEST AND EVALUATION:

A liquid-filled test-chamber was fabricated which contained a reference hydrophone and submerged sound source. A thin polychloroprene rubber diaphragm enclosed the water and was the interface to the “test-dummy.” The rubber’s density and sound-speed are similar to that of water, and it becomes acoustically transparent when sandwiched by fluid structures on both sides. Broadband noise, tonal, or physiological electrical signals were used to ensonify the chamber as various sensors were placed in contact with the interface to quantify acoustic coupling and sensitivity. Testing within SEDD’s acoustic anechoic chamber permitted control of the ambient conditions for evaluating the sensors. Low-noise characterizations were conducted by placing the sensors on the ensonified test-apparatus within the quiet anechoic chamber. A high-noise environment, created by driving a speaker with a noise generator, was used to evaluate the noise canceling or rejection characteristics of the various sensor configurations. The reference standard was a Bruel & Kjaer (B&K) half-inch condenser microphone placed within a stethoscope bell that was modified to receive the B&K microphone. Figure 4 below shows a B&K piston-phone calibration device that reliably produces a 250 Hz, 124 dB SPL, referenced to 20 micropascals in air. Also show is a half-inch B&K microphone with preamplifier and the stethoscope with the modification for B&K insertion.

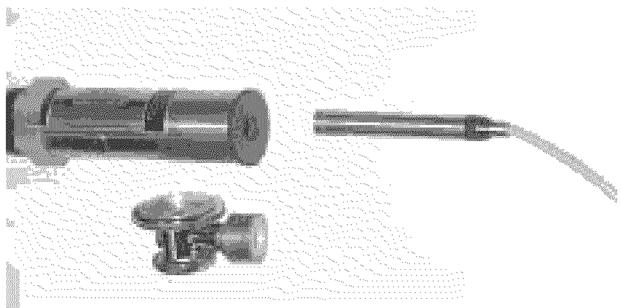

Figure 4: Stethoscope, B&K microphone, and calibrator.

10.0 DATA COLLECTION AND ANALYSIS:

Data were collected with various “breadboard” versions of the acoustic monitoring pad. These data were analyzed with time-frequency analysis, typically short-time Fourier transform analysis (STFT), to evaluate the spectral and temporal characteristics of human physiology, as well as sensor performance. This is a useful method to understand the signature of interest and the often-subtle clues relative to different physiological conditions. Because of the time-frequency tradeoffs associated with FFTs, the short time Fourier Transform cannot detect the multiple components of the first and second heartsounds from the phonocardiogram. Although the Wigner distribution does better, it cannot provide as many features as the wavelet transform, which can separate the aortic valve and pulmonary valve components [Obaidat]. The results of these studies will lead to a better understanding of acoustic correlates to physiology and speed the development of automated detection algorithms to quantify changes in physiology.

11.0 SENSOR TESTS:

Data was collected and evaluated in the three candidate implementation locations (torso, neck, and headband). The subject used his own hand to hold the sensor in contact with the chest and neck, but let the PASGT helmet’s headband hold the sensor in contact with the temple region of the head. Sensors were fabricated using 1 in. and 1.6 in. flexural-disk piezoceramics in an aqueous gel-coupling layer. The neck sensor used an adjustable band with Velcro to hold sensor in the appropriate location. The headband of the PASGT was fashioned with a Velcro strip to permit inserting the sensor between the headband and head. Data from the three locations are shown below in figures 5, 6, and 7. These three data sets include a spoken word count from one to ten, then mouth breathing for the remainder of the data set. Naturally, the heartbeat is always present.

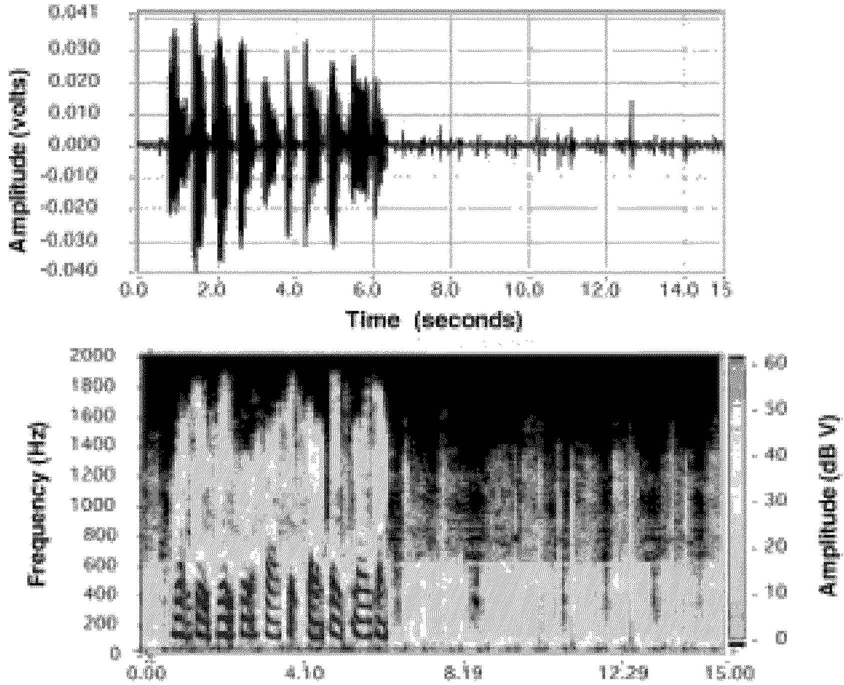

Figure 5: Fluid sensor held at throat for voice count and mouth breaths.

Note in both time-waveform and the spectrogram of figure 5 above the high SNR of voice compared to the "physiological ambient" that includes heartbeats and breaths. The voice is so loud at the throat that the preamplifier gain must be adjusted to one of the lower gain settings to avoid amplifier saturation during speech. This excellent coupling for voice, when combined with the sensor's inherent noise immunity, could make this sensor location ideal for monitoring voice for voice-stress analysis and communications, in addition to physiology. Note also how clear the breath indications are. Figure 6 below shows the same sensor on the chest. Note the SNR of speech and breath is much less, as seen in the time-waveform as well as in the spectrogram representation.

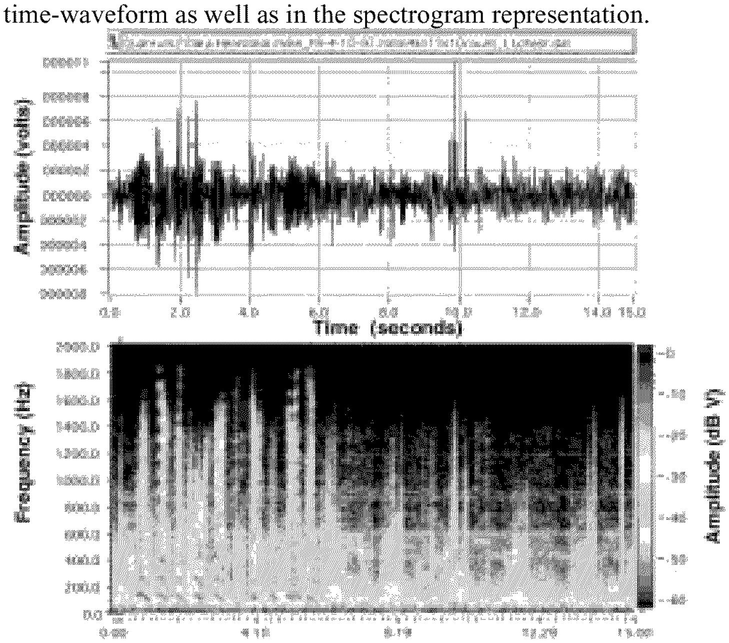

Figure 6: Sensor held at chest, showing heartbeats, breath, and voice count.

Figure 7 below shows how the sensor detects voice and physiology from the temple region of the head. The vocalizations are transmitted through the skull and tissue to the forehead area, and are transduced by the monitoring pad much like bone-conduction microphones do. The breath sounds are also clearly visible, and result from sinus cavity resonances and tissue conduction as well. The temple's pulsations are clearly visible in the low-frequency region of the spectrogram. Voice is much lower in SNR at the forehead than at the neck region, as expected.

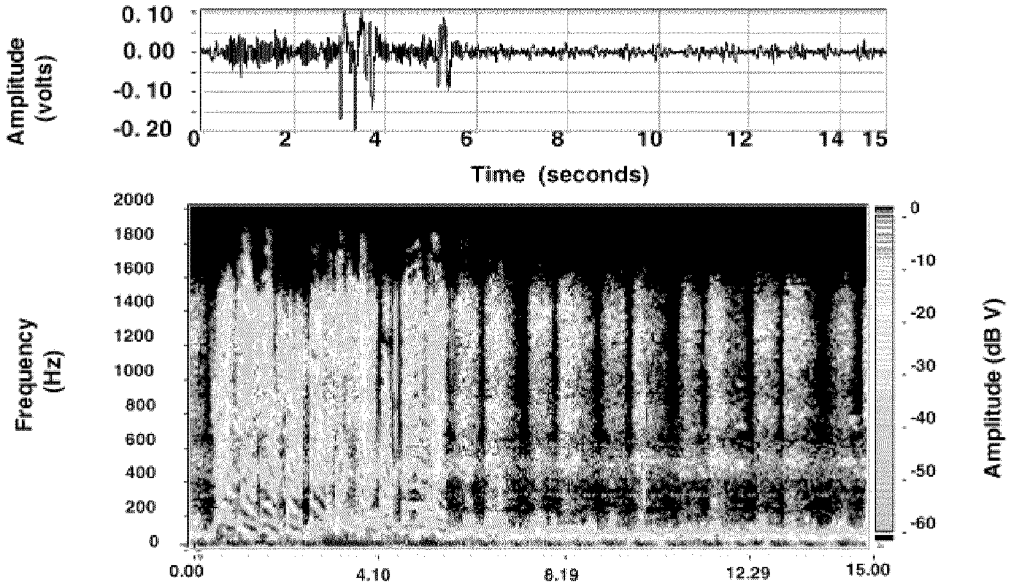

Figure 7: Sensor in headband of helmet, showing voice, temple pulse, and breaths.

12.0 DATA:

In an attempt to gather high-quality acoustic data, along with verifiable "ground truth", data was collected using the sensors described above, going into an 8-channel digital audio tape (DAT) recorder. ARL's goal was to develop a detailed acoustic data set that would be useful for future research and algorithm development. The two soldiers were instrumented with numerous sensors connected to an 8-channel digital audio tape (DAT) recorder within their backpacks. The DAT recorded high-bandwidth physiology and document "truth" data during the training.

Fluid-coupled acoustic monitoring pads were placed on the soldier's chest, neck, and helmet headband to gather their body's acoustic signatures. A calibrated air microphone was placed closely to the front of their mouth's to document breathing, drinking, and vocalizing and ambient noise such as local activity and the presence of vehicles. An accelerometer was used to document footfalls, and the output of a bipolar electrode heart rate monitor was simultaneously recorded to provide heartbeat timing information. By simultaneously recording independent sensors that isolate each truth variable, the acoustic data can be better postprocessed to help discriminate between heartbeats, breaths, footfalls, and other activity.

Figure 8: Boom and neck sensor.

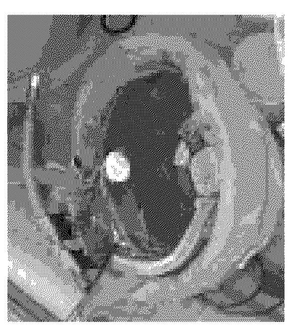

Figure 9: Headband sensor.

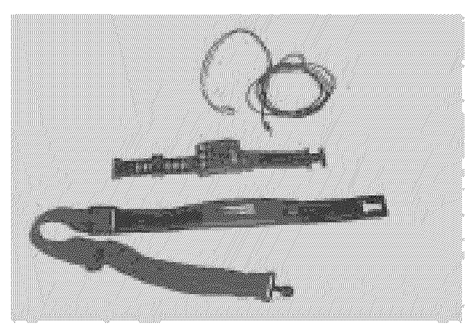

Figure 10: Polar HR Monitor.

Figure 8, 9, and 10 above show a soldier with the fluid-coupled neck sensor and a boom microphone, an internal view of the PASGT helmet with helmet-liner gel sensor, and the Polar heartrate monitor system. In figure 11, (a) and (b) are the time-series and spectrogram representations of human body sounds taken by a fluid-coupled sensor pad attached to the chest of a person walking in open terrain. The figure also gives (c) the heartbeat truth timeline taken by the electrode-based heart rate monitor and (d) the footfall activity timeline taken by an accelerometer.

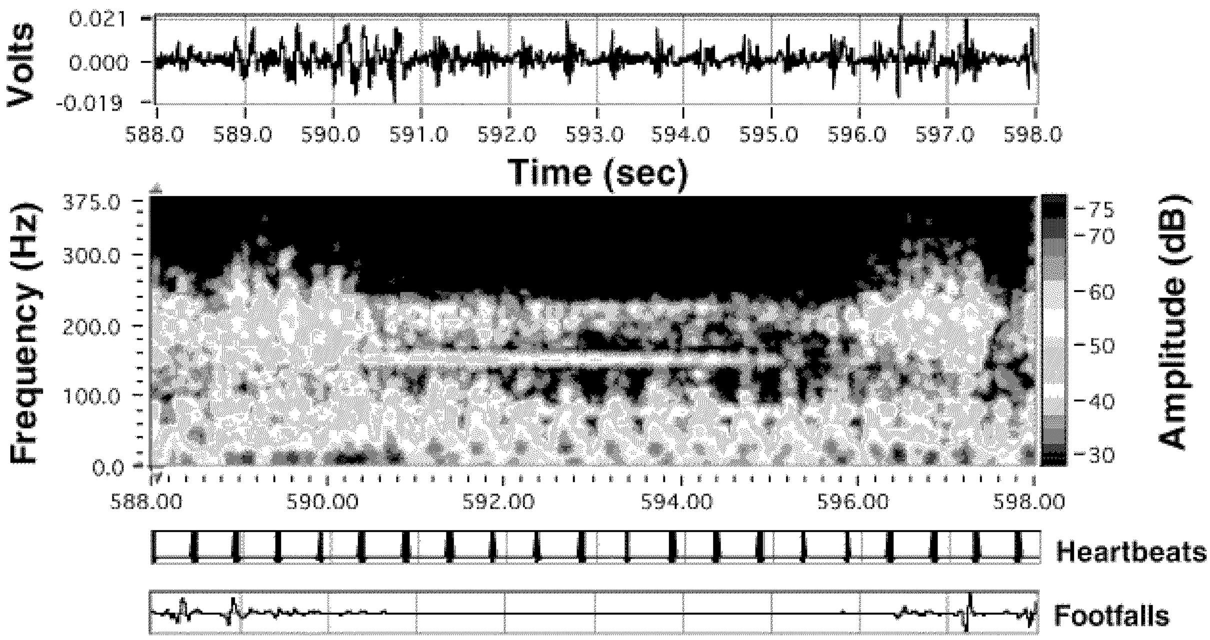

Figure 11: Chest sounds of person walking away from helicopter lifting off.

Footfalls, as seen in the 588 s to 591 s and 596 s to 598 s regions of the accelerometer data, manifest themselves as high amplitude acoustic signals in the 0 Hz to 30 Hz region of the spectrogram and have associate broadband noise as a result of body activity. The timing indicators for the intervals of the footfalls and heartbeats associated with this particular cadence are very similar. The spectrogram also shows that they contain common frequencies as well. This makes the signal separation much more difficult, and will require more advanced methods such as wavelets or higher order spectral analysis. The 591 s to 596 s region (when the soldier is standing still) clearly shows two-component individual heartbeats with minimal extraneous signals. Also shown in the spectrogram are 75 Hz and 150 Hz signals from a helicopter takeoff approximately 100 m away. The presence of a helicopter can be a situational clue for interpretation of physiology. The heart sounds are almost 30 dB higher in amplitude than the airborne-coupled helicopter noise; this indicates a high signal-to-noise ratio of fluid-coupled body signals to ambient airborne noise.

The data shown below in figure 12 are similar to the data above, but of a soldier walking through woodland terrain while conducting a reconnaissance mission in full gear, backpack, LBE, and carrying a weapon. The heartbeats are clearly visible in the 0-1.5 s region of the spectrogram in the 0 to 70 Hz region. Once the footfalls begin, as documented in the lower “footfall” timeline, the heartsounds are somewhat hidden by the higher amplitude signals resulting from impulsive motion, with higher frequency heartsound components still visible in the 30 to 70 Hz region. When listening to this data with headphones, the heartbeats are clearly detectable by the human ear, demonstrating that there is sufficient SNR of heartsounds.

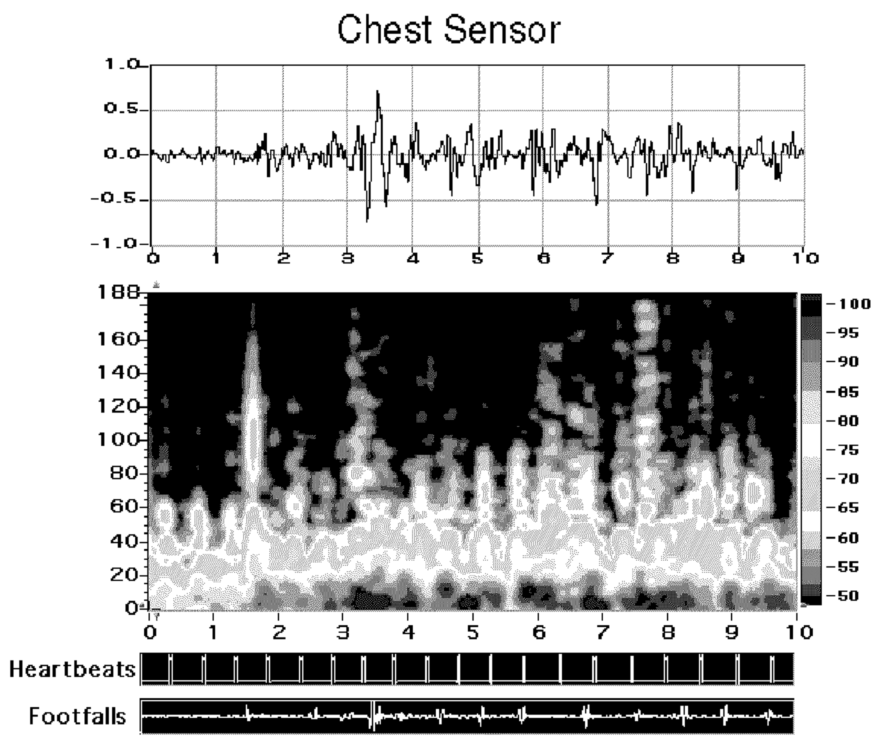

Figure 12: Chest data of soldier walking, heartbeats and footfalls in low-frequency region.

Figures 13 and 14 below also demonstrate the ability of the acoustic sensor to detect footfalls very well, with heartbeats much less apparent during motion.

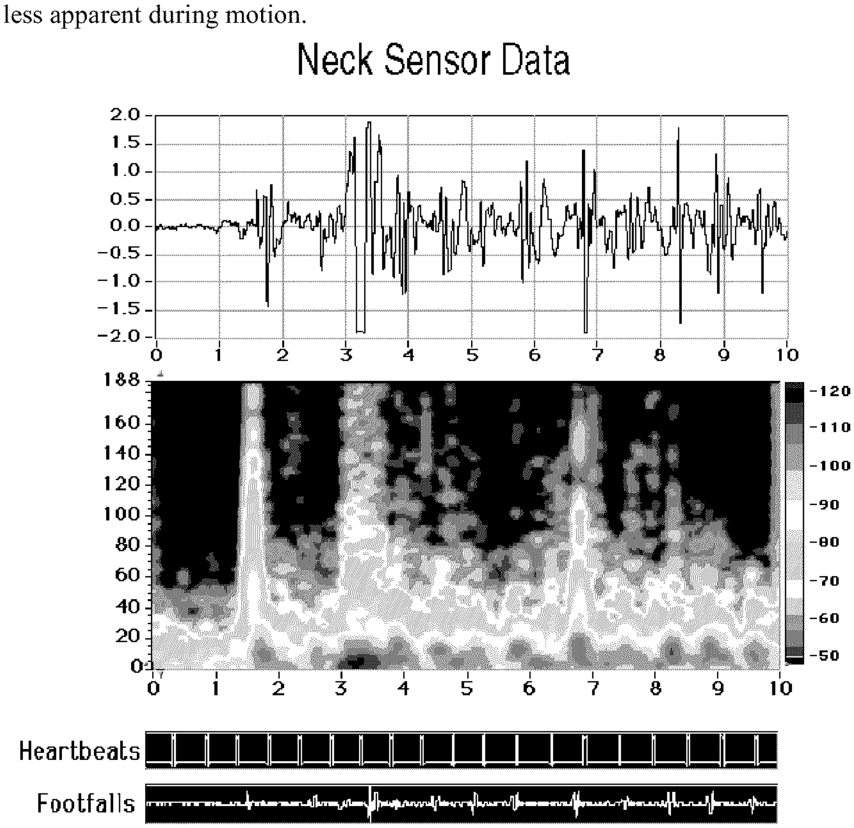

Figure 13: Sensor on neck of soldier during reconnaissance mission.

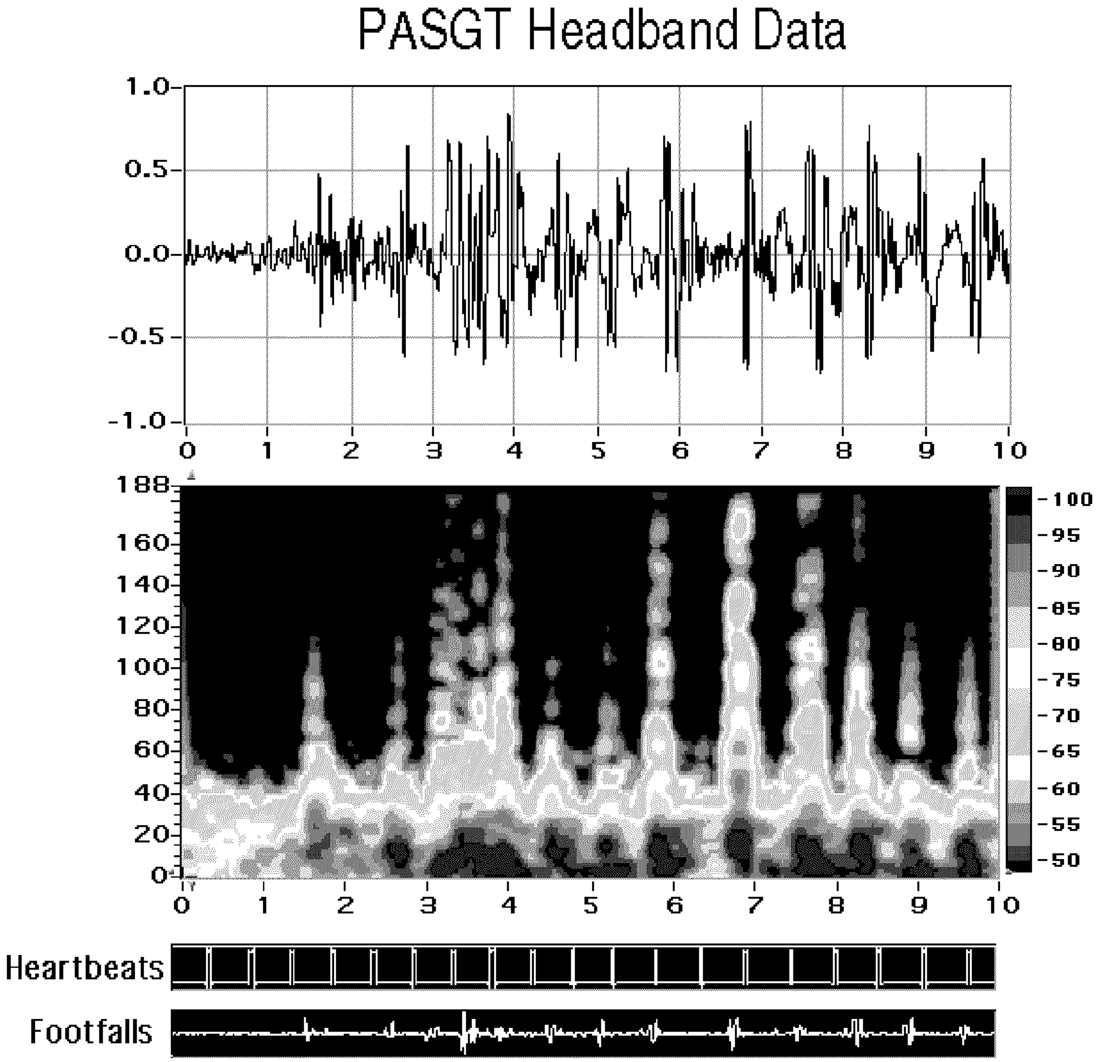

Figure 14: Sensor in helmet headband during reconnaissance mission.

It is felt that a sensor modification, the incorporation of a noise-canceling reference sensor isolated from physiology, could significantly reduce the footfall effect and enhance heartbeat detection. A more detailed look at the data is ongoing, with emphasis on "ground truth" interpretation to extract footfalls from ambient data, as well as focusing on other variables. Temporal and spectral data indicate that it may be possible to distinguish between a footfall and a heartbeat. In hindsight, to enhance data analysis, footfall indicators (accelerometer/pressure sensor mounted to feet rather than in the backpack) would have been very helpful, and will be incorporated the next round of data collection.

13.0 VOICE STRESS:

One voice stress analysis method looks at the time required to induce phonation, and how these onset times vary with stress [Lieberman]**.** Voice onset timing (VOT) is the time delay between the lip opening and the onset of phonation, which is the periodicity in the waveform caused by vibration of the vocal folds. "Voiced stop" consonants such as b, d, and g require the speaker to initiate phonation, whereas the unvoiced consonants p, t, and k are automatic. Lieberman concludes from a hypoxia study that "deterioration in motor control is manifested by reduced separation width." A simple experiment was conducted to determine if the monitoring pad developed for this effort could provide data of sufficient quality to be useful for a VOT study. The data in figures 15 and 16 below represent the results of the experiment.

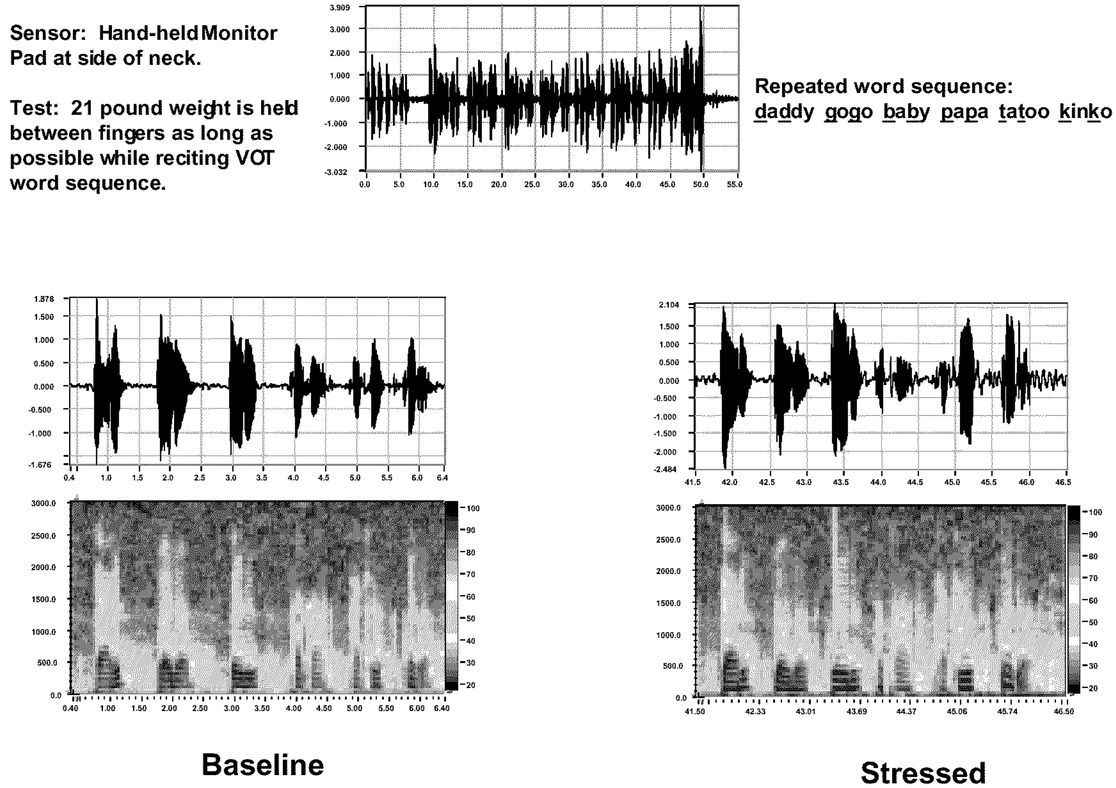

Figure 15: Experimental results of voice stress measurement taken at throat.

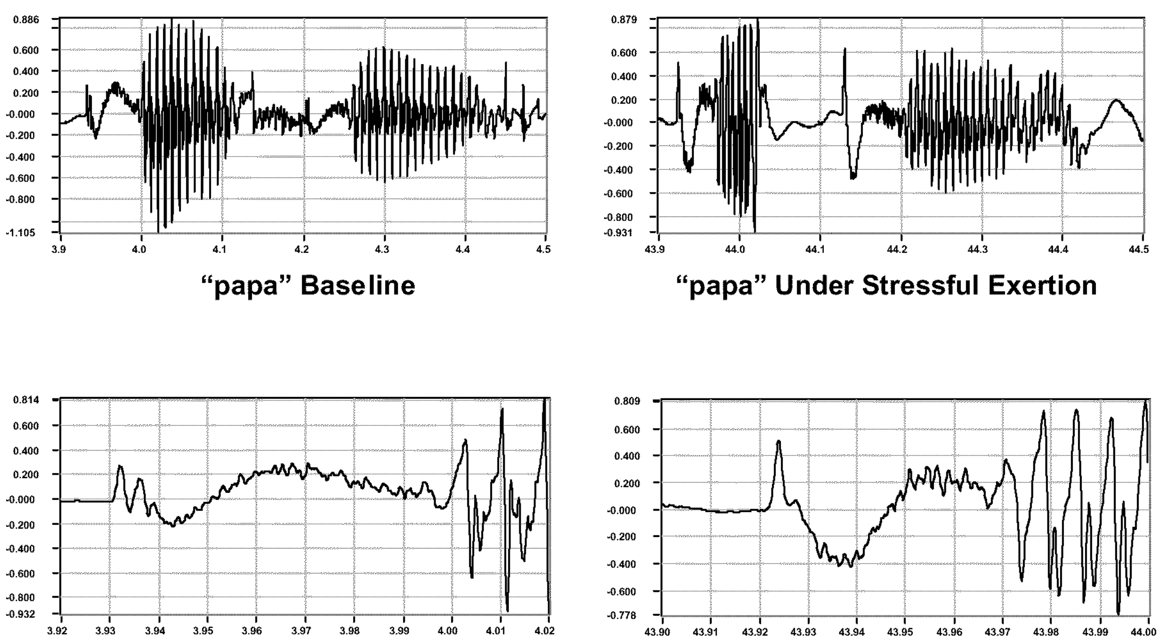

Figure 16: Voice-onset-timing measurement for the consonant "p".

There are other forms of voice stress analysis available that should be considered for soldier stress level evaluations. A micropause approach to speech analysis reduces all features of speech to a pattern of ON's (vowels) or OFF's (consonants or pauses) [Vollrath]. Pattern analysis on the duration of ON's and OFF's are considered to be indicators of different levels of alertness. Shortened micropauses may be an indication of alertness, whereas prolonged micropauses might indicate fatigue. Vollrath et. al. conducted numerous studies on the temporal structure of speech. Hansen is also a recognized expert in the area of voice analysis, primarily in the area of automated detection and how changes in voice stress effect recognition algorithms [Hansen, 1996].

14.0 HIGH SNR:

Figure 17 compares data from a B&K microphone in front of the speakers mouth to that of a fluid-sensor held in contact with the neck. Data were taken simultaneously in a typical office environment. Comparing the amplitudes (dB) of the "voice" to the "non-vocal ambient" noise surrounding the voice give approximately 40 dB SNR for the B&K airborne microphone, and approximately 75 dB SNR for the fluid-coupled sensor. The fluid-coupling represents better than 30 dB improvement in SNR with minimal waveform degradation, as observed by the similar spectrograms and listening to the data through headphones.

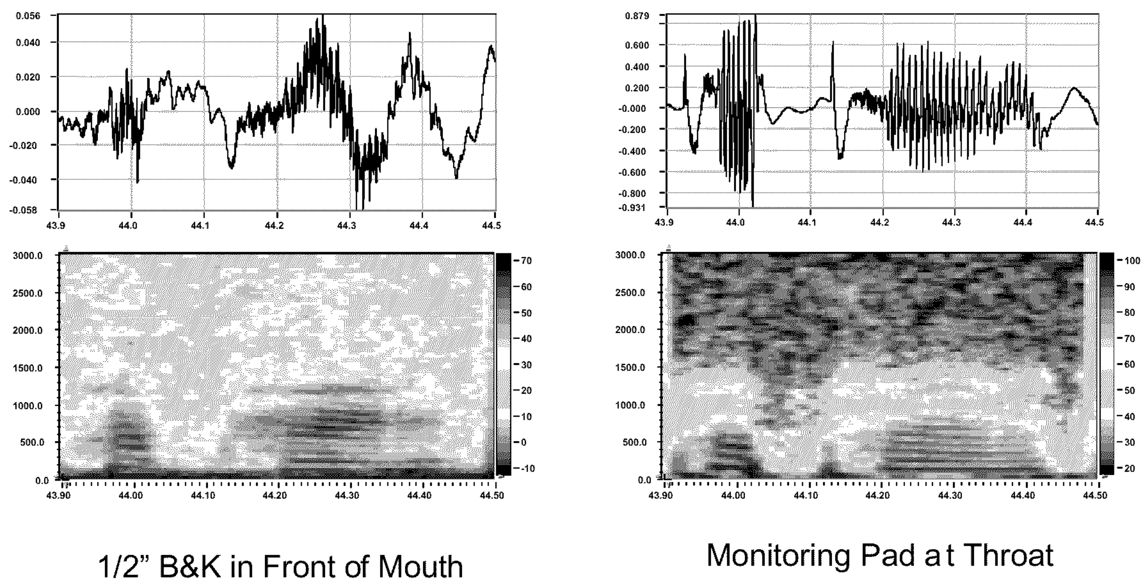

Figure 17: Comparison of spoken word "papa" taken with ambient microphone and throat pad.

15.0 HIGH NOISE ENVIRONMENT:

The detection of physiology and voice in high noise environments is very important for medical evaluation during evacuation, vehicle/aircraft operator monitoring, or voice commands in a noise environment, such as a Tactical Operation Center with multiple speakers. The ability of body-coupled sensors to detect physiology and reduce background noise was investigated, with preliminary results shown below. A 1 in. piezo-ceramic disc embedded within aqueous couplant gel was attached to one side of a speakers neck, and on the other side was a 1/2 in. B&K condenser microphone monitoring the bell-chamber of an air-filled stethoscope. Positioned in front of the person's mouth was a Knowles 1994 microphone, in the boom microphone configuration used previously. Figures 18, 19, and 20 below show simultaneously collected breath and voice data before, during, and after a speaking-subject is submerged in a 105 dB C (ref. 20 micropascals, measured at the throat) noise field inside an acoustic anechoic chamber (hearing protection was required). The person wearing the sensors repeatedly vocalized a 1 to 10 count between the times of 14 and 19 s, 25 to 33 s, 65 to 71 s, and 71 to 77s, and voiced "105 dB" between 47 and 50 s.

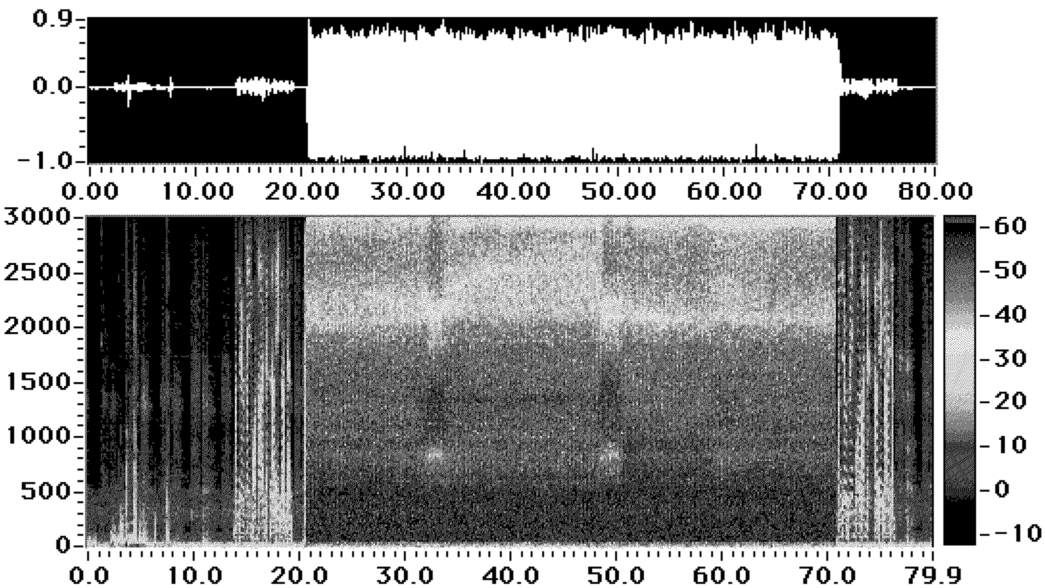

Figure 18: Boom microphone detecting voice in high noise environment (105 dB C).

The boom microphone in figure 18 above does not detect any voice during the high amplitude noise between 20 and 71 s. However, in figure 19 below, the counting is clearly visible throughout the loud noise with the body-coupled gel sensor.

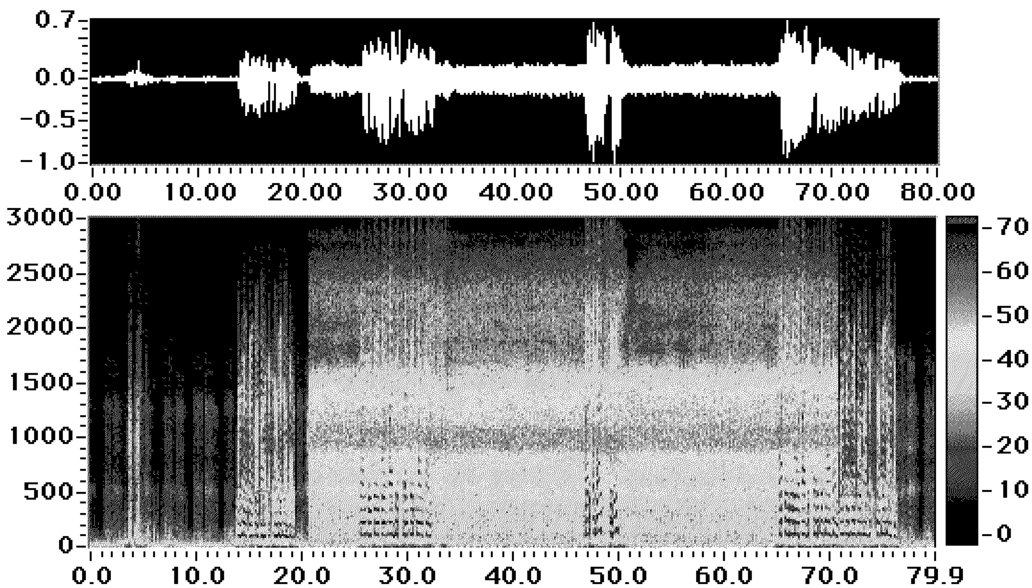

Figure 19: Gel sensor on neck detecting voice in high noise environment (105 dB C).

Note that breath sounds can be seen in the spectrogram between 0 and 14 s and between 77 and 85 s in the gel sensor, and that there is very little low-frequency noise picked up. In contrast, the B&K sensor data, shown below in figure 20, has more low-frequency ambient noise pick-up. The B&K stethoscope combination does detect breaths and voice well, but the ambient noise rejection in the low-frequency region of interest is not as good as the gel sensor.

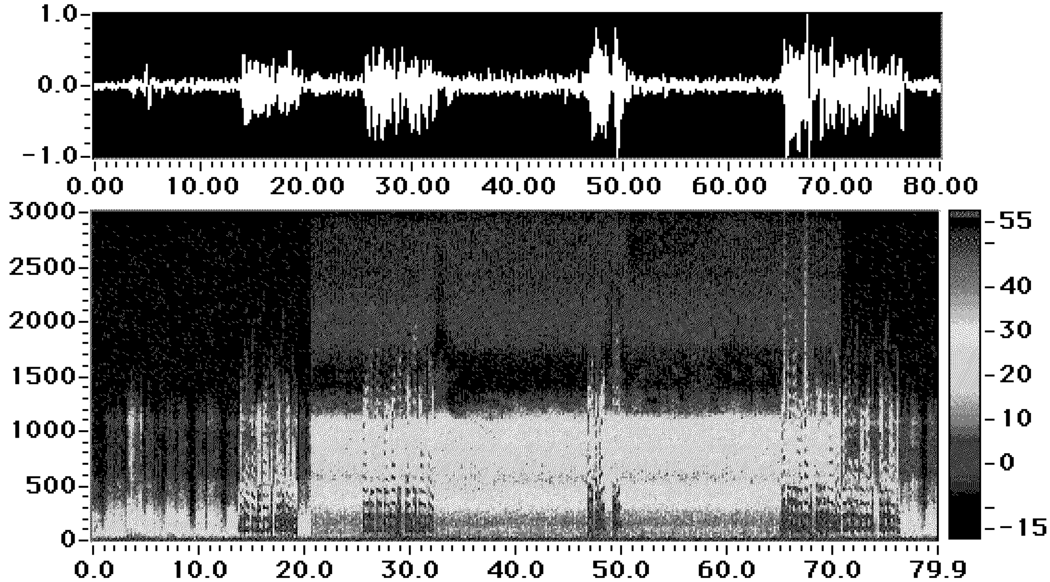

Figure 20: B&K in stethoscope bell detecting voice in high noise environment (105 dB C).

16.0 ASTHMA DATA:

The data below was taken from an 18-year-old male which suffers from asthma. During the subject's asthmatic event, data was recorded with an acoustic sensor comfortably strapped to his throat, and is represented in the time waveform and spectrograms of figures 21 and 22 below. Several breath cycles are shown, followed by a deep inhale and then a forced exhale. This forced exhale was into an AirWatch flow measuring device to measure both peak-flow and forced expiratory volume in one second (FEV-1). Note the asthmatic wheezes present on each breath cycle, seen as time-varying harmonically related spectral lines in the spectrogram. Immediately after the measurement, the subject self-medicated with a bronchiodilator (BD). Another data set was recorded shortly after BD, and the related spectrogram is show in figure 21. Note that the wheezes are gone and that the amplitude and duration of the last breath cycles (peak-flow test) are much higher in amplitude and duration than the reduced capacity breath cycle, demonstrating an acoustic relationship to lung function. Ongoing research at ARL is investigating the correlation between acoustic measurements taken at the throat to tidal volume, peak-flow, and FEV-1 [Kramn].

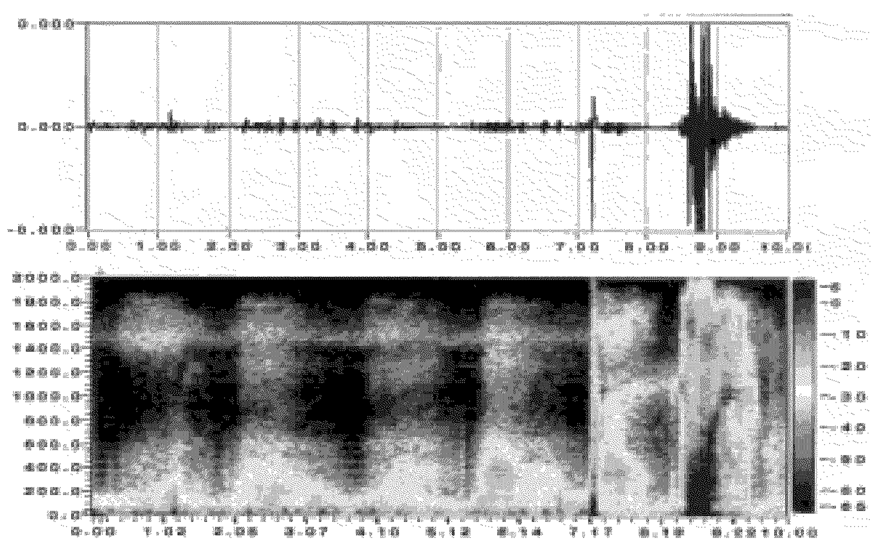

Figure 21: Post-Bronchiodilation of asthmatic.

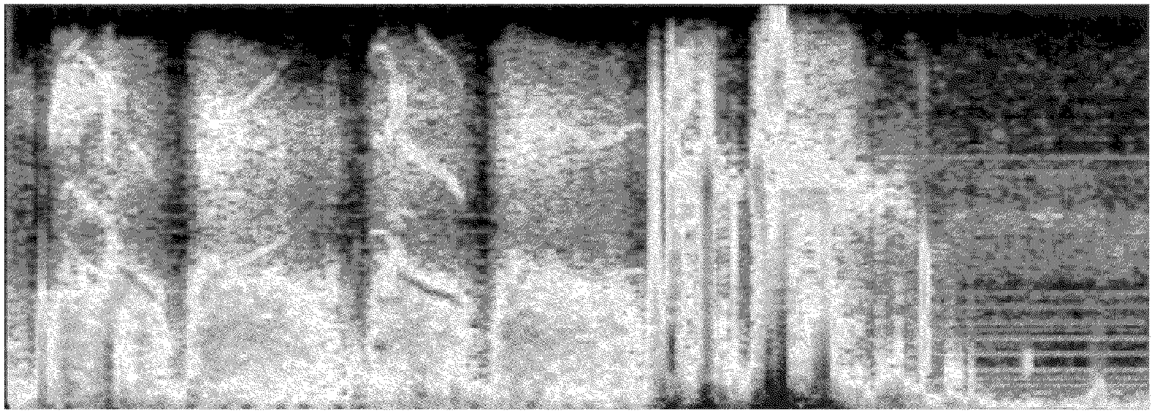

Figure22: Pre-Bronchiodilation of asthmatic.

These two asthmatic data sets show the ability of acoustics to monitor the treatment and recovery of asthmatic episodes. However, these data, when considered in reverse order, could clearly demonstrate that acoustics could determine the onset of asthma by comparing normal breathing to the initiation of wheezes. The acoustic sensor may even be able to detect this condition before the subject is aware of it, due to task distractions or ambient noise. This could be a powerful method to determine how a workers environment or exposure to various chemicals or conditions can trigger asthmatic episodes, and quantify the progression, levels of severity, treatment, and recovery.

17.0 HEART-RATE SOFTWARE:

Before algorithm and hardware development proceeds further, we plan to collect additional realistic data on moving and active soldiers with suitable physiological "ground-truth." This will answer many questions relating to algorithm requirements for noise rejection and SNR, as well as hardware issues such as bit resolution requirements. Dynamic SNR and bit resolution requirements will drive complexity of the algorithm and cost of the hardware. Software to calculate heartrate from the sensor data has begun, and has produced excellent results for data collected in the laboratory. The software algorithm applies band-pass filtering and level detection schemes to calculate inter-beat intervals (IBI) between adjacent first heart-sounds as well as between adjacent second heart-sounds. The algorithm anticipates a range of normal changes in heartrate, and throws out IBI data, which is obviously out of the expected range, and uses an average of the data deemed appropriate. Interference in IBI calculations can result from random acoustic impulsive events such as sensor motion or foot impacts.

Upon redesign of the sensor to evaluate a noise canceling mechanism to reduce footfall and motion interference, a new data set will be collected for the continuance of algorithm development. At this point, we do not want to invest too much effort in algorithm development to extract physiological data from the "noisy footfall data" if a simple sensor modification may improve the signal to noise ratio by limiting footfall effects. There still exists some concern over non-physiological acoustic signals resulting from person's motion and clothing contact. This will be addressed in the very near future.

18.0 FUTURE WORK:

The research and development describe above can be very useful as a remote medical monitor. Obviously, the field medic needs to be able to monitor all the soldiers for health and injury and be able to perform remote triage in the event one or more are injured. The commander would like to be able to monitor all of his soldiers from a manpower/readiness point of view. Trainers would like to ensure the safety of the students while maximizing their training efforts. If each soldier were equipped with an acoustic medical monitor that constantly evaluated each soldier's health and performance levels and transmitted it to a remote location, each of the above observers would be able to utilize the soldier vital statistics. The device would not emit until queried by the medic or leader, or would only transmit when the body worn device determines that a dangerous condition exists, such as heat stroke, hypothermia, or fatigue. Figure 23 shows a hand-held device that monitors multiple soldiers via an RF link. The conceptual device would have embedded diagnostics to help the observer evaluate the vital signs of each soldier. For example, if the sensor detected an impulsive trauma with ensuing heartrate increase and the blood pressure decrease, the processor might suggest a bullet wound has caused excessive bleeding. Slurred speech, muscle shivers, low heart and breath rates might suggest hypothermia. This again demonstrates the effectiveness of an acoustic sensor for extracting many diverse physiological indicators to provide situational clues.

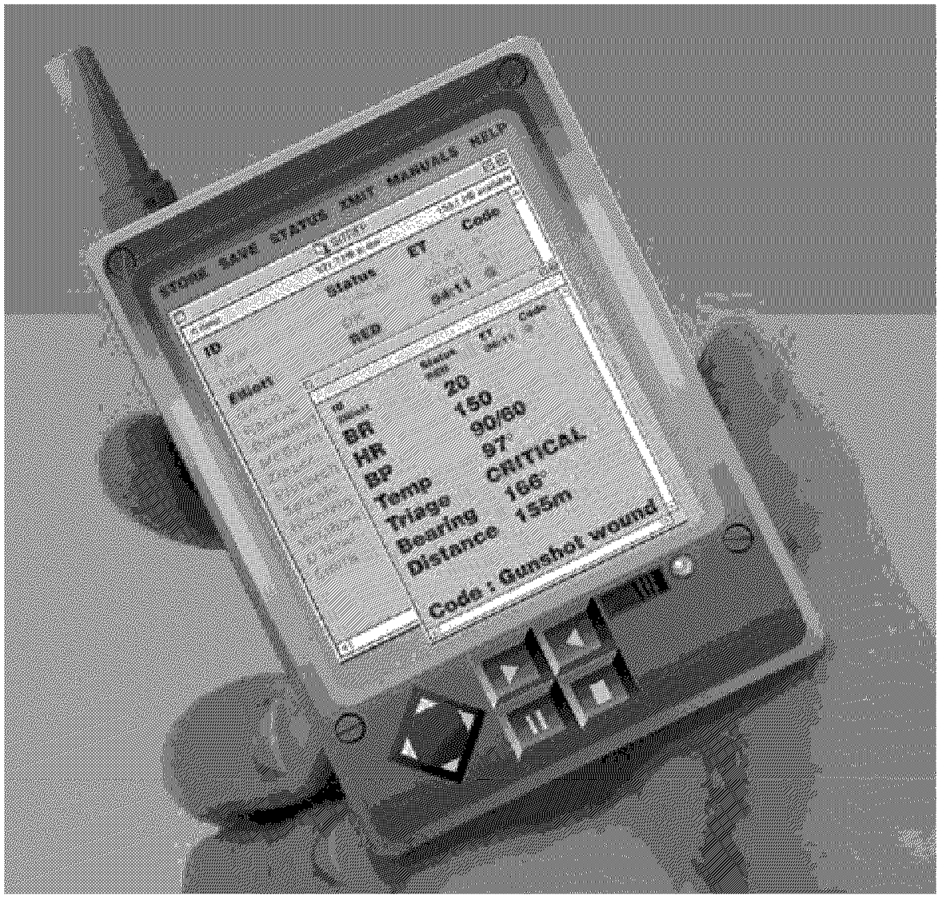

Figure 23: Remote medial monitor display.

19.0 RESULTS AND CONCLUSIONS:

It was determined that fluids and solid gel-material (like a synthetic silicon) have acoustically enhancing properties when used as an impedance matching layer between human tissue and the piezoceramic elements. Both possesses good ambient noise rejection characteristics due to an impedance mismatch between it and air. Although the data collected thus far has not been thoroughly reviewed, it is apparent that the sensors effectively couple to the body and attenuate ambient noise well, as demonstrated by the ability to clearly hear through-the-body voice during a helicopter hover test. However, footfalls appeared to interfere with the detection of heartbeats while walking, in that the acoustic sensor transduces the body forces generated by impact, and create both temporal and spectral characteristics similar to that of heartbeats. Much more work needs to be done on signal analysis and filtering techniques to separate different events.

The use of an acoustic sensor provides a low-cost, lightweight, noninvasive, and adaptable means to monitor many aspects of a soldier's health and activity. Unlike most medical sensor technologies, which look at only one physiological variable, a *single acoustic sensor* can collect information related to the function of the heart, lungs, and digestive tract or it can detect changes in voice or sleep patterns, other activities, and mobility. Algorithms to evaluate data from acoustic sensors can be continuously modified to monitor new parameters, the correlation between dissimilar body functions, other medical sensing technologies, or even the interrelation between the soldier's physiology, the mission, and the surrounding battlefield.

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