A Sensate Liner for Personnel Monitoring Applications

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Abstract

This program develops and demonstrates technologies useful for implementing a manageable cost effective systems approach to monitoring the medical condition of personnel by way of an instrumented uniform hereafter referred to as a Sensate Liner (SL). The SL consists of a form fitting garment which contains and interconnects sensing elements and devices to an electronics pack containing a processor and transmitter. The SL prototype requires fiber, textile, garment and sensor development. The SL textile consists of a mesh of electrically and optically conductive fibers integrated into the normal structure (woven or knitted) of fibers and yarns selected for comfort and durability. A suite of SL garment compatible embedded biological and physical sensors are then integrated into the SL. The initial SL sensor suite is selected to improve triage for combat casualties. Additional SL sensor concepts for medical monitoring will be discussed.

1.0 Introduction

The Sensate Liner for Combat Casualty Care Development Program develops a novel combat uniform (Fig. 1) consisting of a medically instrumented wearable circuit garment (Fig.2) useful for identifying, developing and demonstrating technologies useful for implementing a manageable cost effective systems approach to monitoring the medical condition of combat soldiers by way of an instrumented uniform hereafter referred to as a Sensate Liner (SL). The SL consists of a form fitting two piece jumpsuit which contains and interconnects sensing elements and devices to an electronics pack containing a processor and transmitter. The proof of concept SL includes both biological (vital sign), physical (projectile impact), and environmental (blood loss) in order to depict the casualties status as completely as possible. The goal of the SL program is to develop innovative technological approaches that will provide military forces with enhanced combat casualty care capabilities. The SL is focused on the following areas: (1) flexible elastic wearable printed wiring technology development consisting of - insulated conductive fiber (thread) development; textile fabrication incorporating the insulated conductive fiber with helically woven (applied) optical fiber for penetration alert; process development (design rule generation) for establishing inter-fiber electrical interconnects; high and low resistivity traces; shielded traces; cross seam interconnects; sensor mounting technology; sensor connection technology; distributed chip mounting technology; processor attachment and interconnect technology; and inter-garment electrical and optical interconnect technology (2) biological sensors selected from (and consideration restricted to); Blood Pressure, Pulse Rate (Heart Rate), Cardiac Output (Derived), Respiratory Rate, Electromyogtaphic Activity. (3) Physical Sensors including - barrier penetration (optical and/or electronic for projectile penetration sensing); acoustic (0-5mHz for high speed projectile detection, classification and localization); bleeding, blood loss and blood oxygenation; and motion. (4) intra- sensor data fusion techniques for biological damage assessment, (5) Ultra low power alert and monitoring technologies, (6)

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Computer Automated Design for custom mass production of individually tailored and equipped SL's (7) Advanced concepts for unusual or exotic sensors or SL fabrication technologies including but not limited to micromachined sensors, smart (intelligent) sensors, and inter sensor communication technologies.

The Sensate Liner (SL) mesh forms a conductive back plane (Fig. 3) hosting and integrating sensors for biological phenomenon such as blood pressure, pulse rate (heart rate), etc. ; physical sensors including - barrier penetration, motion, position etc.; environmental sensors such as temperature, etc. The initial proof of concept suite includes sense modalities for heart rate, respiration, torso penetration (occurrence, classification and localization), and motion. Of particular interest is the detection and location of high speed projectiles penetrating the human body. Experimental results utilizing polymer acoustic transducer arrays indicate entrance wound locations can be detected with an acceptable degree of accuracy. The SL, while individually tailored, will utilize computer automated design technologies such as laser scanning amenable to custom mass production.

2.0 Wearable Circuit Garment Development

2.1 Historical Background: A Weavable Computer: Concept to Reality

John Kay's invention of the flying shuttle in 1733 sparked off the first Industrial Revolution, which led to the transformation of Industry and subsequently of civilization itself. Yet another invention in the field of textiles – the Jacquard head by Joseph Marie Jacquard (circa 1801) -- was the first binary information processor [1}. The Jacquard proved to be the inspiration for Charles Babbage's Analytical Engine. He envisioned numbers flowing in and out of the Analytical Engine under the control of a sequence of steps or program embedded in punched cards. Lady Ada Lovelace, Babbage's friend and admirer, expressed this intrinsic relationship between textile science and computer science best when she said "Babbage's Analytical Engine weaves algebraic patterns just as the Jacquard loom weaves flowers and leaves". Although Babbage did not live to complete the work on the Analytical Engine, he developed the concepts of input/output, memory, arithmetic and control, which form the basis for present day computers [2]. The Jacquard card spawned the Hollerith punched card, which set off the second industrial Revolution – the information processing or computer revolution. Thus the field of textiles has been instrumental in bringing about one of the most significant technological advancements known to mankind [1]. It is only appropriate that the field of textiles take the next evolutionary step towards integrating textiles and computers by designing and producing a weavable computer that is also wearable like any other textiles.

2.2 Circuit Garment Research & Development Objective

With regards to the circuit garment development itself, the goal is to produce elastic wearable structures with globally distributed sensors and randomly positioned sensors, i.e., a truly flexible and wearable woven computer! Although the initial application is for combat casualty care, the information processing capability of the garment renders it equally useful for other applications including analog-computing!

2.3 The Circuit Garment Requirements

The sensate liner or flexible computer is being designed to meet the performance requirements associated with combat usage and typical textile characteristics of durability, wearability, usability, maintainability and manufacturability, and the integration of the twin objectives realized through interconnected sensors. The information processing garment should be an "integral" garment, flexible and comfortable to the wearer.

2.4 Circuit Garment Structure and Design

The structure of the proposed wearable computer has been designed from first principles using a QFD-type (Qualify Function Deployment) approach to meet the performance requirements. It will consist of a single-piece garment similar to a regular T-shirt. The initial prototypes will be of medium-size to fit a 38-40" chest. The penetration sensing component will be built into the structure using an innovative process to ensure the integrity of the garment and the sensing capabilities of the system. The structure, as shown in Fig. 4, will also contain regularly spaced yarns acting as sensing elements, and precisely positioned yarns for carrying signals from the sensors to the Personal Status Monitor (the CPU that "processes" the sensing information and communicates with the off-site base unit). The structure will be "form-fitting" to ensure that the garment is unobtrusive in its use in combat and is comfortable to the soldier.

2.5 Realizing the Wearable Computer: Concept to Reality

Research is being carried out to realize the proposed design of the wearable computer. Based on an extensive analysis of materials properties, appropriate materials have been chosen for the various components of the wearable computer. The appropriate fabrication technology has been identified for the production of the structure. An a-Prototype – an integrated one-piece wearable garment -- has been created and is currently being tested for its information processing characteristics.

Based on an evaluation of the experimentally observed electo-optical performance of the circuit garment, the design and process parameters will be suitably refined to create the truly wearable computer!

3.0 Circuit Garment Surface Penetration Localization

While the garment provides a backdrop for a variety of sensors, primary emphasis is being placed on the utilization of embedded sensors for ballistic penetration and location detection on the upper torso. This section details the design philosophy, successes to date, and remaining challenges of this SL segment.

To facilitate integration of embedded sensors to a flexible garment, ILC proposed the use of conductive thread systems as the mechanism to detect and locate penetrations in the garment, and to interface other potential sensors. This soft approach would provide a garment that stretches to fit the physique of the wearer, yet provides a conductive circuit backbone sewn directly to the fabric. The conductive thread is integrated into a grid of rows and columns within an upper torso garment. Each row and column is scanned (via microprocessor multiplexing) for end-to-end continuity. When a penetration occurs, the conductive path of the thread is broken and detected by the microprocessor, which in turn, provides grid location in (X-Y coordinates) indicating where the penetration physically occurred relative to garment and anthropomorphic features.

Furthermore, multiplexing of the garment circuit allows the detection of multiple penetrations with a resolution of 1 to 2 mm particle size. This critical aspect provides sensitivity for detection of small grain ballistic penetrations, the most common form of projectile in the battlefield wound scenarios.

3.1 Materials

Material selection is vital to the development of the SL garment , including the selection of a highly conductive thread system and the garment materials which are conformal, comfortable, and durable. Ideally, the thread system is insulated to protect against shorting or corrosion, and is easily and uniformly integrated to the garment using high volume stitching and fabrication techniques.

To date, ILC has evaluated a variety of conductive thread systems which are compatible with high volume integration to an SL garment, and is currently evaluating methods to sheath or insulate the fibers. Evaluation of a variety of base fabrics for the garment is also in process, focusing on lightweight cotton-polypropylene/lycra materials which provides high elongation, a conformal fit, and moisture wicking from the body. The garment material and circuits are launderable and extremely durable. Circuit interfaces to the processor are accommodated using a robust flexible film bus which is buried within the garment seams, hidden completely from the wearer.

3.2 Experimental Results

Bench tests have successfully demonstrated the penetration sensitivity and processor multiplexing capabilities of the soft circuit concept on representative test panels . A Full scale garment fabrication has been demonstrated which will incorporate a 14 row x 18 column upper torso front panel grid, integrated to a Dupont Coolmax lightweight fabric (Fig. 5). Microprocessor code is complete for multiplexing of the garment, and thin film bus fabrication is in process which will provide the interface of the conductive thread to the processor, and a platform for incorporation of other sensors to the garment

4.0 Automated wound analysis

The sensate liner concept, consists of a flexible, wearable circuit board, capable of supporting a variety of sensors that will monitor the vital signs of the wearer and automatically detect and characterize a wound in real time. The liner is intended to be worn as an undergarment, without significantly encumbering the wearer. Signals from these sensors (Fig. 6) will be monitored, acquired, processed and interpreted in a wearable, Pentium-type computer. Information is then condensed and either stored or transmitted to a suitable response unit for processing and resource allocation in a timely fashion.

The components if this system presently under development at MRC, focus on the task of automatically detecting, localizing and characterizing a penetrating wound (wound analysis). A variety of sensors are being investigated that can perform these tasks in the soldier-based environment, in combat situations, without enhancing soldier detectability and with a goal of zero false alarms. The sensors receiving primary attention monitor the stresses and pressures associated with the liner penetration process as well as the disruption of human tissue by the penetrating round. The use of active ultrasonic techniques for post impact diagnostics is also being considered. In addition, a very low power pulsed radar system is being evaluated that has the potential for locating the pre and post impact projectile.

4.1 Piezoelectric gage detection and localization of impact/penetration

A simple system that is particularly well suited to the present application covers the liner garment with discrete, slightly overlapping piezoelectric film gages. These gauges have a very high frequency response capability and are thin, light, flexible and routinely commercially available at very low cost. The most common film utilized, PVDF, a material that produces a large electrical charge when stressed. No electrical excitation is required so that the gages place no electrical power demand on the batteries of the self-contained system. These gages can cover the entire sensate liner, and, when arranged in a fish scale pattern, will yield complete coverage without significantly altering the flexibility of the garment. The electrically conducting fibers of the woven liner garment can be used to deliver the signal(s) from the film patches to a microprocessor and eventually to the wearable computer.

For the present application the film gages are operated in the charge mode in which the charge generated by the piezo material energizes a simple RC circuit composed of the capacitance of the film (Order 1 nanofarad) and a load resister which will dictate the rate of discharge of the gage. By selecting a low time constant, on the order of 1 microsecond (1,000 Ohm load resistor), the system cannot respond to relatively slow loading events with rise times greater than a few microseconds. This will render the system insensitive slow loading events that may result from falls, bumps and blows while retaining high sensitivity to the fast loading associated with the penetrating round. Upon penetration of the film gage, especially by an electrically conducting projectile, the film is shorted with a near instantaneous discharge to zero. For very fast, sharp rounds, it appears desirable to introduce thin cladding on the film so that the time from the onset of loading to discharge is somewhat extended. Cladding with a suitable plastic, on the order of 1/4 millimeter thick, seems desirable.

The voltage on each film gage is monitored continuously in customized microprocessors that compare the voltage on each gage to an adjustable, pre-set voltage. If the voltage on any one or more gages exceed that level, a data acquisition system is activated and the responses of the gages that caused the trigger will be stored. This trigger will also cause the wearable computer to activate and prepare to receive multiple channels of data, process data as necessary and signal a medical support unit. From the activated film gages alone, the entry location of the wound is localized, and if present the exit wound location. In this case the wound track is approximately identified and comparison to a stored anatomical model such as the human phantom in the Soldier Protective Ensemble Computer Aided Design (SPE/CAD) system will permit the automatic identification of a wound severity code for transmission to a medical support unit.

4.2 Determination of Wound Track and Wound Severity

When a projectile passes through a fluid medium, noise fields radiate into the medium, originating primarily in the wake and boundary layer of the projectile and, at low speeds to a lesser extent from the pressure generated by the projectile tip. As the sound speed is exceeded, the pressure pulse from the tip can overshadow the other sources. Human tissue is a multi-phase combination of fluids and visco-elastic/plastic solids that are expected to generate a variety of pressure fields upon penetration by a projectile. It is reasonable to assume that these noise fields will contain characteristic patterns that may be used to identify details concerning the projectile producing these fields. Actually, the details of the round, i.e., size, shape, velocity etc., is less important than the extent of tissue disruption along its trajectory. For example, an ogival round at velocity, V, flying end-on stable will produce a very small wound canal whereas the same round, heavily yawed or tumbling, will produce an order of magnitude more tissue damage. Ideally one would derive the temporary and permanent wound track cavities rather than projectile details.

To exploit these possibilities, human tissue simulant, consisting of ordnance gelatin ranging from 10% to 20% solid by weight, is being instrumented and subjected to projectile impacts. Ordnance gelatin of these concentration has been shown to successfully simulate human tissue relative to projectile penetration depth. A variety of pressure sensing devices, ranging strain gage steel diaphragm to ceramic piezoelectric transducers and piezoelectric film gages with various backing materials have been used in preliminary experiments. Strain gage, ultrasonic and broad band piezo-ceramic transducers were rejected early because of difficulty in mounting these rigid and heavy transducers on the ordnance gelatin without loosing contact early on. This problem of weight and mount-ability would be particularly troublesome for application of these devices to the skin of an active soldier. The effort has therefore focused on the use of piezoelectric film patches, similar to the ones used to detect the impact but now configured for a much longer time constant to track the low frequency aspects of these pressure fields.

A number of ballistic tests have been conducted, using primarily piezoelectric film patches mounted on the surfaces of nominally right circular cylinders made of ordnance gelatin. The transducers were "coupled" to the surface using mineral oil or petroleum jelly and held in place by elastic bandages. The cylinders were impacted by hemispherically blunt cylinders of .22 caliber and 9 mm diameter and by 30 caliber FMJ, ogival carbine rounds (30.06). Data from the film patches was recorded in a 200 MHz, 4-channel digital storage oscilloscope (DSO). This data is then transferred to a Pentium computer for analysis and storage. At this time data is being generated and data processing techniques are being evaluated to form a basis for algorithm development.

Ealuation of the recorded data suggests that there are rather well defined characteristic features associated with the penetration processes tested to date. Amplitude profiles exhibit identifiable features that can be used for calculations of arrival times of these features at the various probe locations. The differences in arrival times translate into differences in distance traveled by the disturbance and thus reveal the location of the origin of the disturbance relative to the known gage locations (Fig. 7). Differences in amplitude of these characteristic features can also be used to determine distance to the disturbance by using the measured attenuation characteristics of the ordnance gel of different concentrations.

In the eventual soldier-based sensate liner system the DSO will be replaced by tailored and dedicated data memory chips capable of A to D conversion and storage at the required data rates. This data will then be downloaded into the RAM and probably the hard drive of the wearable computer for processing. At this time we are determining constraints on how much data processing can be accomplished before compression and transmission to the medical support unit.

The above discussion has focused primarily on the acquisition and management of data derived from piezoelectric film patches and gages. It is recognized that active ultrasonic inspection of the post impact casualty can reveal specific wound details and the location of the resting residual penetrator if any. Laboratory inspections of post impact ordnance gelatin blocks using active ultrasound have demonstrated this capability very well. Practical problems with this approach include the need for an inactive casualty, ultrasonic transducers that are well coupled to the skin and a rather energetic ultrasonic pulser. This approach is expected to place significant demands on power and the data processing unit.

The use of a micro impulse radar (MIR), developed by Lawrence Livermore National Laboratory, for this application has not been fully evaluated. These units are small, inexpensive and operate on minute power requirements. Although the system is judged to have potential for identifying and locating an incoming round, the task of discriminating between penetrating and non-penetrating projectiles is significant. Also, the piezoelectric film patches can effectively accomplish this task with virtually zero power requirement. The use of the MIR concept for the post impact evaluation however will be investigated in detail. It offers several advantages over the active ultrasonic approach in its much lower power requirements and in its inherent capability to perform precise ranging measurements, without the need for widely separated multiple receivers. The applicability of this system for monitoring details and activities in a living body has been demonstrated by its application as a Sudden Infant Death Syndrome alarm, that warns of stoppage of breathing or heart beat in an infant.

The residual penetrator clearly has sufficiently different dielectric properties to be detected within human tissue. Debrided tissue along the wound track of a projectile is also expected to be detectable although not as readily as with ultrasound. Laboratory tests on simulant will be performed in the laboratory and eventually, clinical tests on gunshot victims are likely.

Investigations are being initiated to assess the data needs and the requirements for data processing capability from the soldier-based computer system. Preliminary indications suggest that these requirements are well within the capabilities of the wearable Pentium computer.

4.3 Experimental Results

Measurements from acoustic sensors employed individually and grouped as arrays will be presented which indicate the feasibility of detection, classification, localization and tracking of battle field penetrants in combat soldiers.

5.0 Summary

This work contributes to the state of the art in wearable computers and biomedical technology in two distinct areas. First and probably most significant is the area of patient wearable biomedical sensor integration. The wearable circuit garment concept makes cost effective comfortable patient monitoring a reality. The extension to other wearable computer applications is straightforward. Secondly, for combat casualty care applications the torso penetration sensor suite demonstrated here allows improved estimates of biological damage to a Medic Dispay (Fig. 8) as well as physiological monitoring to improve triage and battle field medical intervention.

The circuit garment has been designed to incorporate a variety of other sensors to the fabric substrate, making further use of the flexible bus, sewn circuitry, electro-optic backplane mesh and processor technology. Demonstrated sensors include piezo-electric film sensors for motion, temperature, or other bio-feedback sensing. The fabric substrates are also suitable for incorporation of optical sensors, reflective or camouflage materials, communications networking, or fiberoptic cable interfaces. Further development of the SL Garment will include methods of customizing fit of the garment to exact anthropomorphic features of the wearer (using full body laser scanning technologies) and incorporating a suite of sensors to the garment to demonstrate the global features available for combat casualty monitoring.

The SL garment is comprised of off-the-shelf components, with a proven history of comfort and durability. Integration of sewn circuitry using high volume computerized application techniques has been demonstrated and optimized for the current materials. Two unique applications have been demonstrated under this contract:

1) The ability to "sew" a circuit onto an expandable fabric substrate, and detect small particle penetrations. This technology has a wide variety of potential applications where leak and/or penetration detection AND location are critical in a fabric component.

2) The ability to interface microprocessor technology to the conductive backbones, and interface of other bio-feedback devices that may prove critical for battlefield combat casualty care operations.

Further development will provide a high confidence level in user acceptance of the Sensate Liner *to the standard suite of military battlefield gear.

6.0 Acknowledgments

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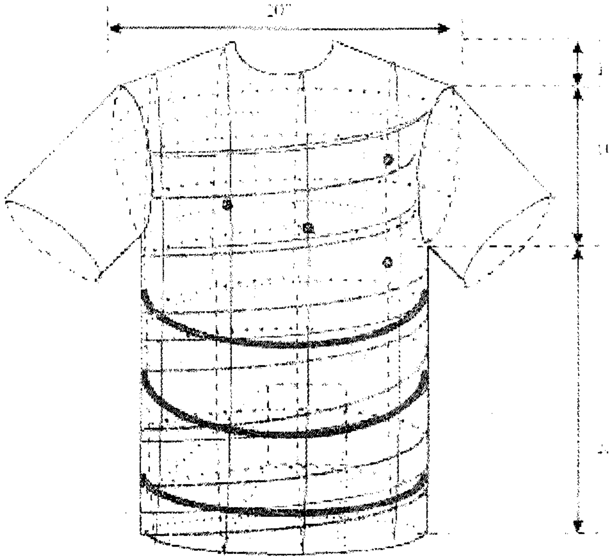


Figure 1. Sensate Liner Concept.

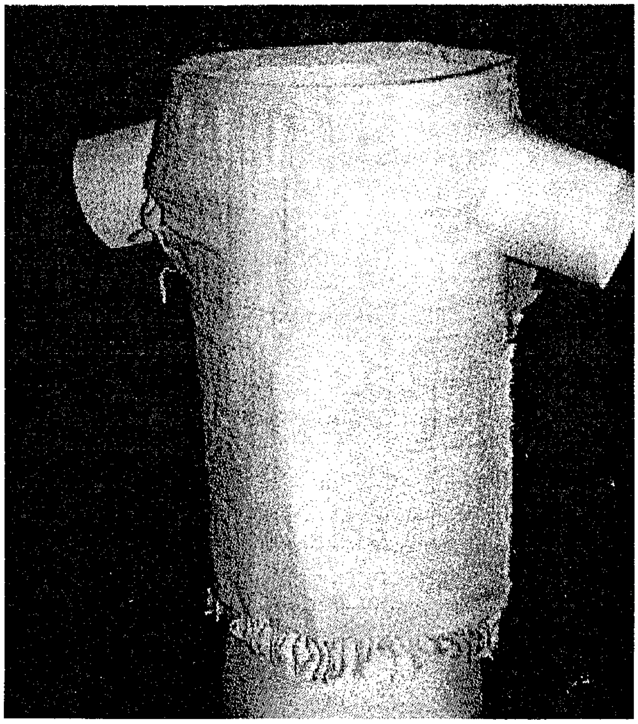


Figure 2. Sensate Liner Prototype.

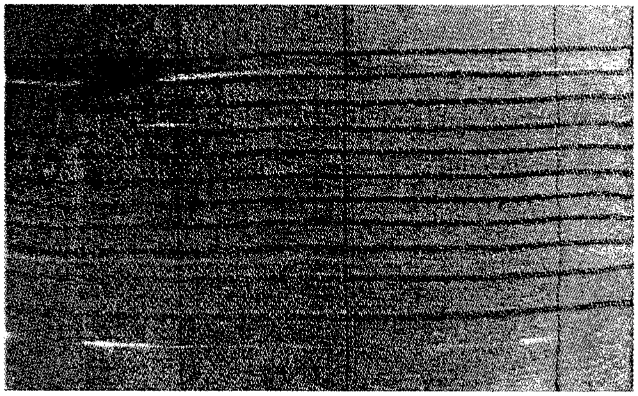


Figure 3. SL Close up - electrical and optical fiber grid.

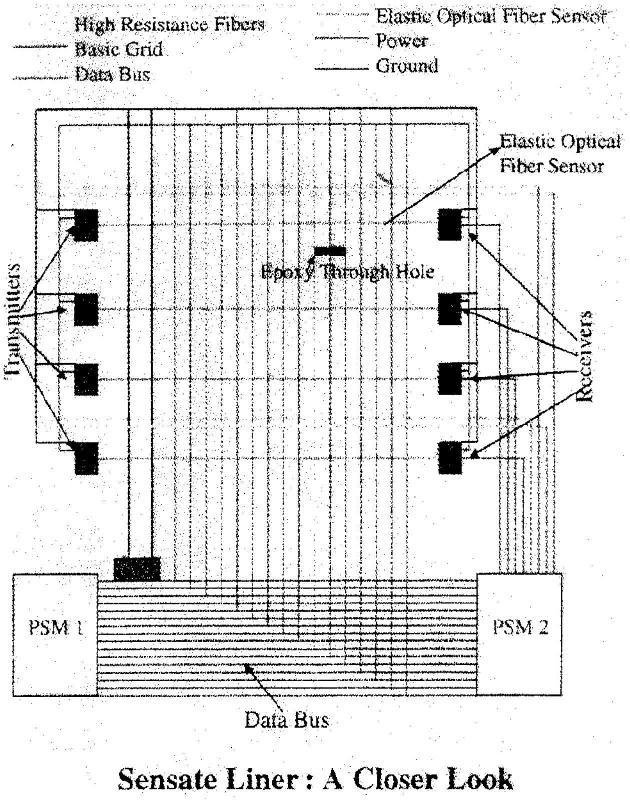


Figure 4. SL Schematic Diagram

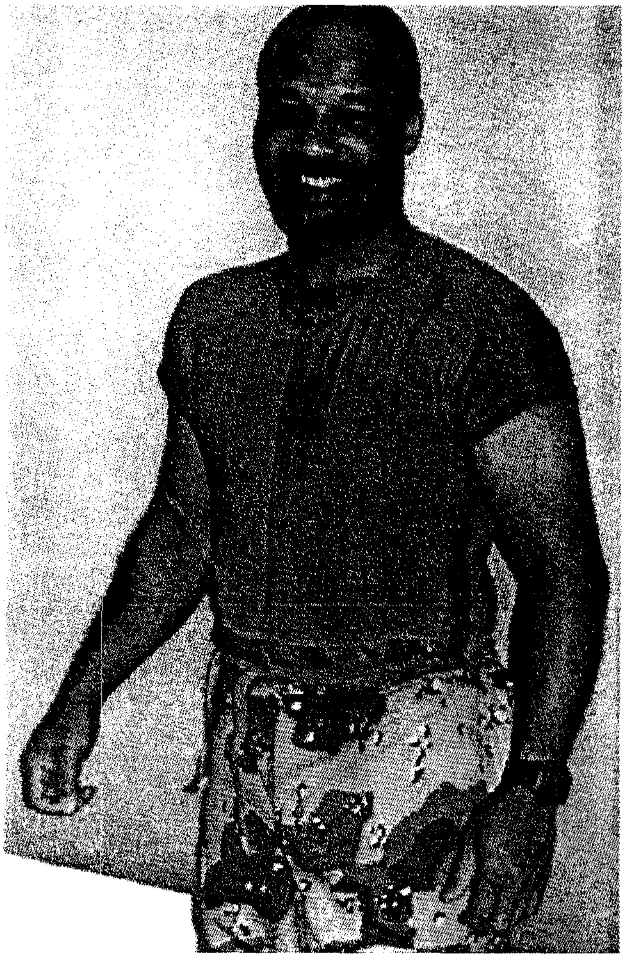
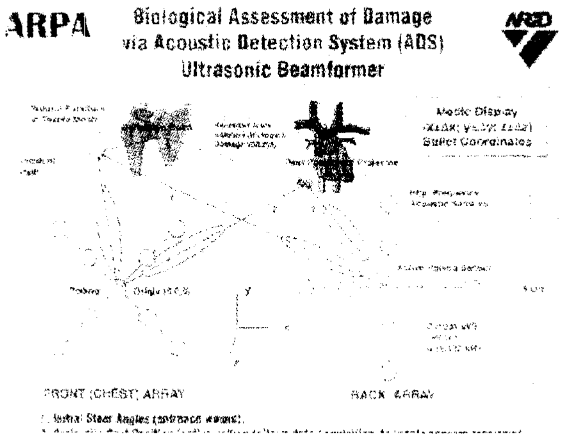


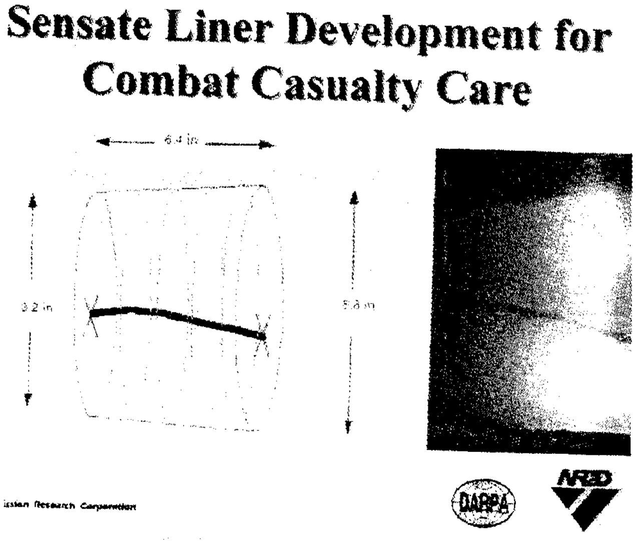
Figure 5. Tactile Torso Penetration Overlay.



ARPA

Biological Assessment of Damage via Acoustic Detection System (ADS) Ultrasonic Beamformer

Figure 6. Ultrasound Detection of wound track .



Sensate Liner Development for Combat Casualty Care

Figure 7. Wound track detection experiment.

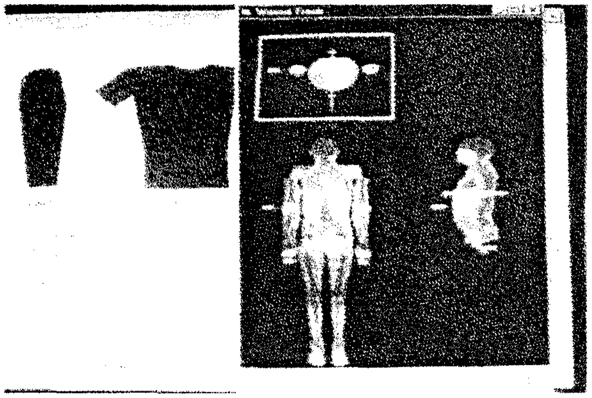


Figure 8. Medic heads up display.