NASA Smart Surgical Probe Project

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ABSTRACT

Information Technologies being developed by NASA to assist astronaut-physician in responding to medical emergencies during long space flights are being employed for the improvement of women's health in the form of "smart surgical probe". This technology, initially developed for neurosurgery applications, not only has enormous potential for the diagnosis and treatment of breast cancer, but broad applicability to a wide range of medical challenges. For the breast cancer application, the smart surgical probe is being designed to "see" a suspicious lump, determine by its features if it is cancerous, and ultimately predict how the disease may progress. A revolutionary early breast cancer detection tool based on this technology has been developed by a commercial company and is being tested in human clinical trials at the University of California at Davis, School of Medicine. The smart surgical probe technology makes use of adaptive intelligent software (hybrid neural networks/fuzzy logic algorithms) with the most advanced physiologic sensors to provide real-time in vivo tissue characterization for the detection, diagnosis and treatment of tumors, including determination of tumor microenvironment and evaluation of tumor margins. The software solutions and tools from these medical applications will lead to the development of better real-time minimally-invasive smart surgical probes for emergency medical care and treatment of astronauts on long space flights.

KEY WORDS

Multi-modality microsensors, intelligent medical conditions and treatments database, intelligent virtual interface, smart surgical probe

1. INTRODUCTION

NASA Mission to Mars – In preparation for this three-year-long mission, NASA is planning to develop smart medical robotics incorporating not only multi-modality microsensors for gathering data non-invasively or minimally-invasively from astronaut in real-time, but an intelligent database of medical conditions and treatments for various situations ranging from appendicitis – to stroke – to myocardial infarction – to acute subdural hematoma. Advanced information technologies will be used to provide virtually instantaneous characterization and diagnosis of medical conditions; the robot's effectors (lasers, aspirators, device implanters) – guided by the wealth of information gathered and compared to the database in real-time – will be able to treat the vast majority of emergency medical situations requiring surgical intervention without additional input from NASA Mission Control Center (which is precluded by the communication transmission delays to and from Mars).

The task of conducting emergency surgery at a site remote from the surgeon (such as on Mars) presents issues of (1) sensors at the operative site, (2) effectors at the operative site, and (3) communication between the sensors and the effectors. In the traditional Operating Room setting, the surgeon is the "device" that resolves all three issues. Depending on the remote site, these three issues may be very different. At one extreme lies image-guided stereotactic brain biopsy, where the "remote site" is but a few centimeters away – within the patient's skull. Here the surgeon uses imaging data as the "sensor", a biopsy needle as the "effector", and is himself the "communicator" between the sensor and the effector. At the other extreme lies surgery in space, where the earth-bound surgeon is handicapped not only by being remote from both the sensors and the effectors, but also by the time delays in communicating between the sensors, the surgeon, and the effectors (on the order of tens of minutes, rather than the milliseconds where the surgeon's nervous system integrates "sensing" and "effecting" during traditional surgery).

On the issue of effectors for remote surgery, surgical robots are evolving rapidly. Initial applications involve robots as aids to the surgeon (e.g. AESOP – Computer Motion, Santa Barbara, CA) and robots that perform strictly-defined automated tasks, such as reaming out the femur under CT-guidance for artificial hip surgery (e.g. RoboDoc – Integrated Surgical Systems, Davis, CA). More recently, robots have become effectors guided by the surgeon, allowing minimally-invasive and remote cardiac surgery (e.g. DaVinci – Intuitive Surgical, Mountain View, CA and Zeus – Computer Motion, Santa Barbara, CA). In neurosurgery, image-guidance has been combined with robotics to automate procedures such as brain biopsy and the placement of deep brain stimulation electrodes for movement disorders such as Parkinson's Disease (e.g. NeuroMate – Integrated Surgical Systems, Davis, CA).

On the issue of communication between sensors and effectors for remote surgery, a solution for real-time surgery in space is challenging. With transmission times on the order of tens of minutes each way for surgery performed on a long duration mission (e.g. Mars mission), it is not feasible for the surgical "communicator" to be an earth-bound surgeon. A more viable approach (one with potential applications for surgery on Earth) is to have the "surgeon" be a device which incorporates the sensors, the effectors, and the communication between sensors and effectors. This device (which we call the "NASA Smart Surgical Probe") would travel with the astronauts onboard their spacecraft, and would perform the diagnostic and therapeutic aspects of surgery in space relatively autonomously (i.e. with only basic input from the onboard astronauts, who would not include a surgeon).

On the issue of sensors for remote surgery, advanced chemical and biological microsensors based on Micro-Electro-Mechanical (MEMS) and carbon nanotube technologies are rapidly emerging. These advanced microsensors have great potential in that they exhibit fast response and show extreme sensitivity for some chemicals and biological markers. One possibility is a device to provide accurate, high resolution feedback on tissue properties to the surgeon, in addition to the visual information provided by high-resolution cameras. Since transmission delays make this impractical for extraterrestrial surgery, the NASA Smart Surgical Probe (NSSP) Project has focused on sensing capabilities that provide this information directly to the effector (surgical robot).

The NSSP premise is that multi-modality data from an array of microsensors – integrated in real-time with advanced information technologies (e.g. hybrid neural networks/fuzzy logic algorithms) to an intelligent medical conditions and treatments database – would be an effective solution to the issue of real-time communication between sensors and effectors. Moreover, surgeries conducted using this solution would be safer and more efficient, whether in space or on Earth.

The remainder of this paper describes the steps taken to develop the NSSP. Two surgical applications are discussed, and brief descriptions of the systems under development are provided. Finally, conclusions and future plans are presented.

2. APPROACH

To lay a solid foundation for surgery in space, the approach taken is to first address surgical challenges in the hospital and to test the NSSP in a controlled hospital setting. Real issues are addressed and the technologies that result will benefit society directly. Two medical challenges were selected: (1) enable neurosurgical operations to be performed more safely and accurately; (2) enable real-time in vivo detection and diagnosis of breast cancer.

Neurosurgery challenge: Since the early 1990s, the limitations of image-guided neurosurgery for procedures such as stereotatic brain biopsy, tumor excision, and functional neurosurgery have become increasingly well recognized: (1) brain shift and/or fiducial movement may render the pre-operative scan invalid; (2) important structures (e.g. blood vessels) may be violated on the path to a deep brain target; (3) apart from electrophysiological recording, no information is provided about the target when it is presumably reached. Intraoperative magnetic resonance imaging (MRI) is a cumbersome and expensive solution, provides only limited data regarding the status of deep brain (or neoplastic) tissue, and is scarcely a feasible solution for surgery at remote sites either on Earth or in space. To overcome these limitations, the NSSP combines image-guidance with data from multiple microsensors at the probe's tip as it approaches an intracranial target – data then processed in real-time by hybrid neural networks/fuzzy logic algorithms to characterize and provide information on tissue properties.

Breast cancer challenge: When a suspicious lump is detected in a breast, a core biopsy or fine needle aspiration (FNA) is usually performed, and the extracted tissue is prepared and analyzed by a pathologist. If cancer is diagnosed, the surgeon will perform surgery to remove the malignant tumor, including a margin of surrounding healthy tissue to ensure complete excision. The diagnostic process can be inefficient because of the time delay when an on-site pathologist is not immediately available. Moreover, if the tumor is to be removed, the surgeon (not knowing exactly the extent or reach of the tumor) may excise a sizeable margin of surrounding healthy tissue in one portion of the specimen and still have close or positive margin on a different edge of the excised tissue. Clearly, what is needed is a better way to detect and diagnose breast cancer, and to do so in vivo in real-time. The NSSP addresses this need by combining image-guidance with 1) data from multiple microsensors at the probe's tip as it approaches a tumor target, 2) data from external sensors which provide information on tumor features, and 3) other relevant patient information, to form a high dimensional dataset – dataset then processed in real-time by hybrid neural networks/fuzzy logic algorithms to characterize and provide information on tissue properties.

The choice of sensing modalities depends on the specific medical application. For initial consideration in neurosurgery, we have chosen optical spectroscopy, pressure/resistance, electrophysiology (spontaneous activity, evoked activity, and bioimpedance), laser Doppler cerebral blood flow (CBF), pH-PO2-PCO2-temperature, and data from a 1 mm diameter neuroendoscope as the primary sensors whose data are synthesized into a unique signature for each tissue (e.g. gray matter, white matter, blood vessel, tumor). Various situations can be distinguished: (1) tissue type; (2) tissue status (e.g. normal vs. neoplastic); (3) tissue condition (e.g. normal vs. ischemic). For initial consideration in breast cancer detection and identification, we have chosen noninvasive ultrasound imaging to guide probe insertion and provide information for 3D tumor reconstruction and feature extraction, optical spectroscopy, pressure/resistance, bioimpedance, laser Doppler blood flow, interstitial fluid pressure, pH-PO2-PCO2-temperature, and relevant patient information (e.g. lymph node status, prior history of breast cancer)

3. IMPLEMENTATION

This paper is focused on the design and development of the NASA Smart Surgical Probe (NSSP). In designing such a device, an early and important question is to decide exactly what the key parameters are and what sensing technologies exist that can be integrated into the probe. We performed extensive literature searches to identify the key parameters, prioritized them relative to what sensor technologies are available and feasible for our applications, and developed system prototypes for proof-of-concept testing. Where possible, within cost constraints, sensors were custom-designed and combined with other sensors to form a small diameter probe (1-2.5 mm).

The robotic neurosurgery device was designed to 1) overcome the danger of severing a critical artery in the probe's path, 2) enable computer-controlled insertion of selected sets of microsensors to improve the accuracy of characterizing and identifying tissue types , and 3) enable effectors of various kinds to be used (e.g. tissue excision, drug delivery). Figure 1 illustrates the robotic neurosurgery device – the first drive mechanism is used for positioning the outer cannula and a set of microsensors; the second drive mechanism is used for retracting/inserting other sets of microsensors and effectors. The device is mounted on a standard Brown-Roberts-Wells stereotaxic frame. The display screen depicts the probe's current location relative to stacks of pre-operative MRI scans of the patient. Figure 2 depicts the robotic device schematic.

Initial experiments were conducted using pig brain and foods with similar stiffness properties. Figure 3 shows the experiment setup. A comparison of resistance to probe insertion (i.e. ~ stiffness) for 'pig brain vs. soft tofu' is given in Figure 4. Multiple measurements of each substance are superimposed to show the degree of repeatability although the probe's path was different for each measurement.

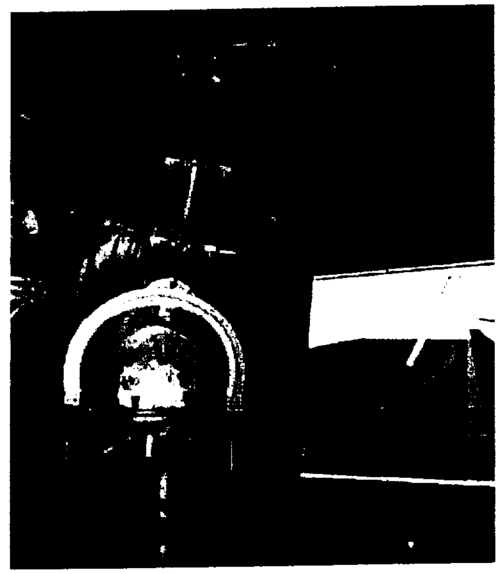

Figure 1. Robotic Neurosurgery. The NSSP probe is attached to a standard BRW stereotaxic frame, and driven to the target under computer control using localization information from pre-operative MRI scans.

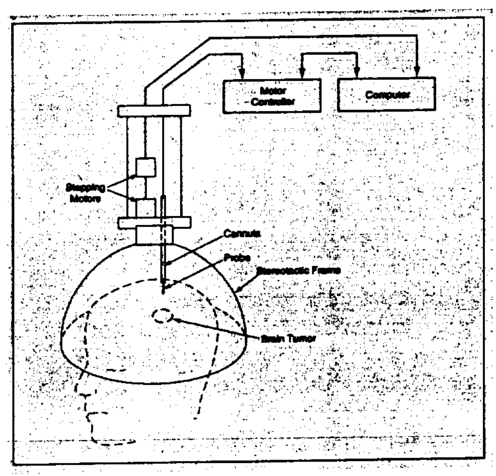

Figure 2. Robotic device schematic. One drive mechanism inserts both the outer cannula and a set of microsensors; the other drive mechanism can be used to retract and replace the set of microsensors with effectors or other combinations.

Figure 3. Pig Brain Experiment.

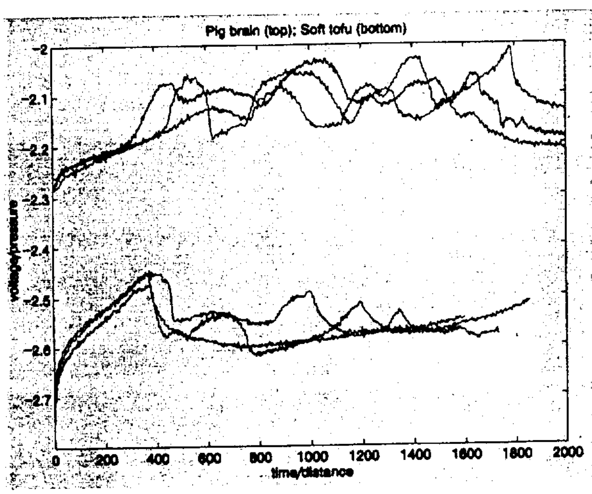

Figure 4. Resistance to probe insertion experimental data. Upper traces are superimposed pig brain measurements; lower traces are superimposed soft tofu measurements.

The breast cancer project was created in response to a NASA Memorandum of Understanding with the United States Department of Health and Human Services, Office of Women's Health, to transfer NASA technology for the fight against women's diseases. We are collaborating with Stanford University School of Medicine to develop the smart surgical probe technology for breast cancer detection, diagnosis and treatment. Figure 5 shows the NSSP probe attached to a mechanical arm. Figure 6 depicts a user-friendly intelligent virtual interface for displaying real-time information on tissue properties. Figure 7 shows the NSSP probe and ultrasound sensor used for image guidance and 3D tumor reconstruction / feature extraction.

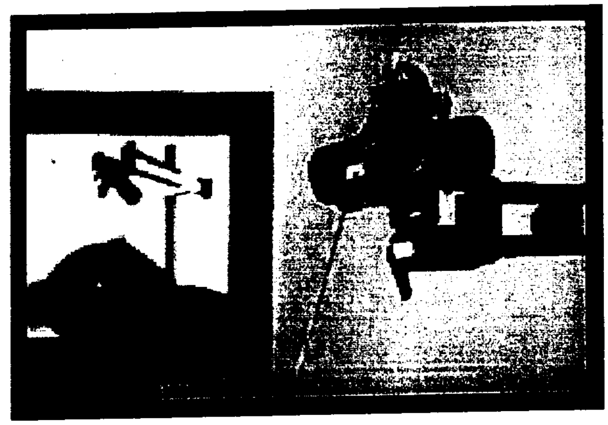

Figure 5. NSSP probe for breast cancer detection and diagnosis.

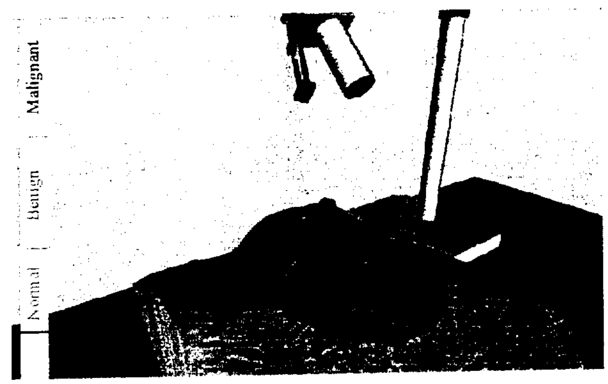

Figure 6. User-friendly intelligent virtual interface. Real-time display of tissue properties.

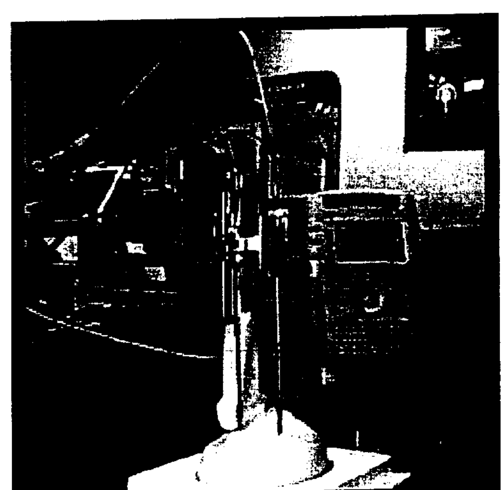

Figure 7. NSSP breast cancer testbed. The NSSP probe is attached to mechanical arm and driven manually, or under computer control, to target under image guidance. The ultrasound sensor is also used for 3D tumor reconstruction and feature extraction.

Example data of optical reflectance measurements is given in Figure 8. The measurements were made of normal tissues (i.e. liver, muscle, fat, brain) in rat specimens. For comparison, Figure 9 gives example data of optical reflectance measurements of mammary tumors (MCF-7 cell line) in rat specimens. The spectra signatures are all distinct. Figure 10 illustrates parameter clustering for various tissue types. The axis parameters were selected from a principal components analysis of the optical reflectance traces.

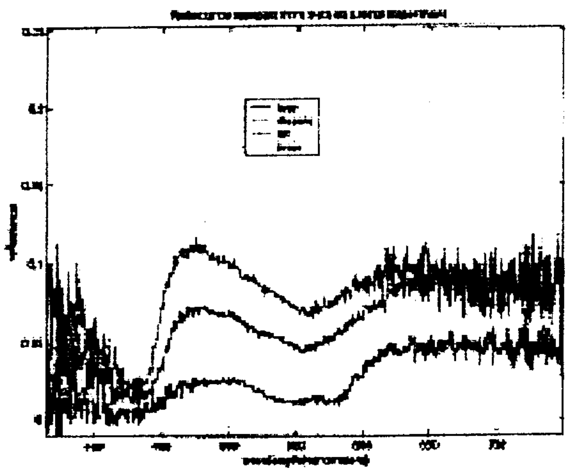

Figure 8. Optical reflectance experimental data for "normal" tissues in rat specimens. (Color legend: blue for liver, red for muscle, green for fat, yellow for brain.)

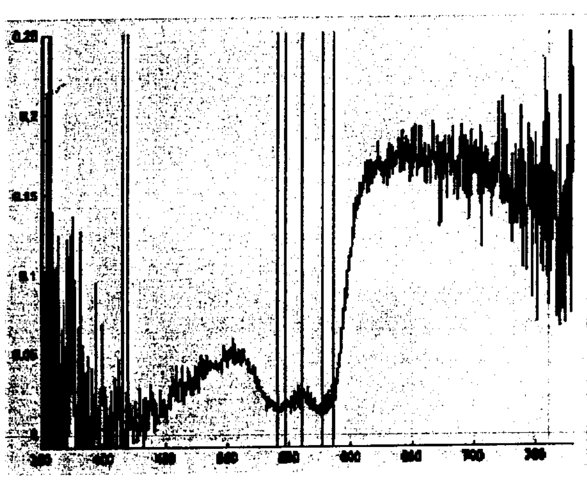

Figure 9. Optical reflectance experimental data for mammary tumor (MCF-7 cell line) in rat specimens. Vertical lines are reference chemical and biomolecular absorption bands of relevance to breast cancer.

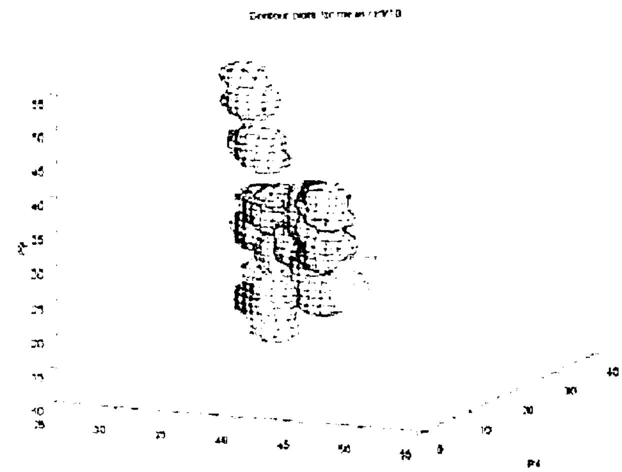

Figure 10. Example of parameter clustering for various tissue types. The axis parameters were selected from a principal components analysis of the optical reflectance traces. (Color legend: blue for liver, red for muscle, green for fat, yellow for brain, magenta for nerve.)

Future microsensors for breast cancer detection, diagnosis, and prognosis will include MEMS and carbon-nanotube-based sensors. In collaboration with the National Cancer Institute (NCI), NASA Ames is employing carbon nanotube technology (CNT) to develop sensors for cancer diagnosis, and is currently working to attach to CNT an identified probe molecule that will serve as signature of leukemia cells (Figure 11).

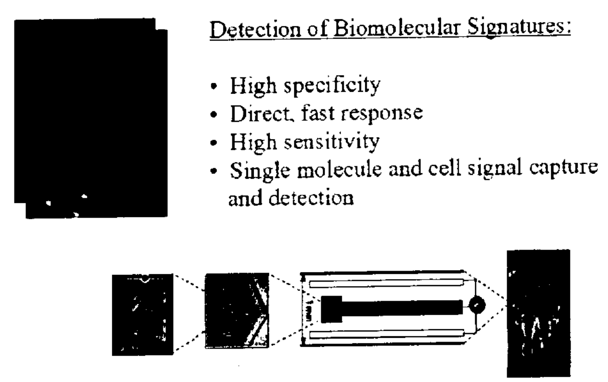

Figure 11. CNT-based sensors under development to detect biomolecular signatures. NASA is collaborating with NCI to develop sensors for cancer diagnosis. (graphics - courtesy of M. Meyyappan, NASA Ames Research Center).

The NSSP information flow diagram is illustrated in Figure 12. The smart surgical probe software (e.g. hybrid neural nets / fuzzy logic algorithms) processes data coming from various sources (internal probe, external sensors, relevant patient information), characterizing tissue properties in high dimensional space in real-time. Fuzzy logic technology is used to process qualitative data such as sonographic features (e.g. margins, internal echoes, edge shadowing). The medical conditions and treatments database is then accessed, and based on an adaptive intelligent cost function, the optimum solution is returned. The cost function varies depending on probe position (e.g. in normal tissue, external to tumor, internal to tumor) and the sensing modalities employed.

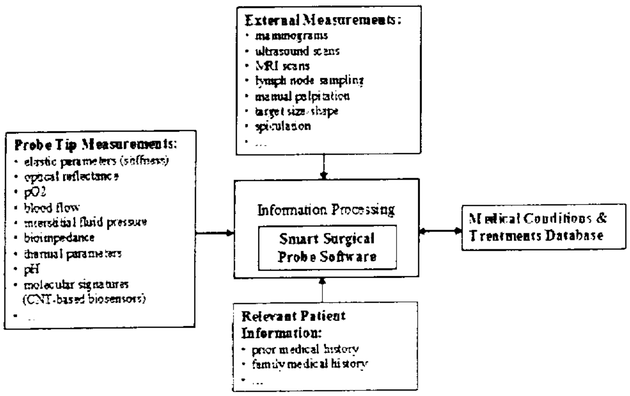

Figure 12. Information flow diagram. Data processed by smart surgical probe software is linked to a medical conditions and treatments database to provide real-time expert information.

4. SUMMARY AND CONCLUSIONS

Surgical tools in use today provide limited diagnostic feedback. For example, brain and breast biopsies are performed with tools that have limited or no sensing capabilities. These tools are guided to the target using MRI scans, ultrasound imaging or mammographic localization. Tissue samples are then extracted, processed and analyzed by a pathologist. The NSSP technology under development has the potential of providing detection/diagnostic/prognostic information (biopsy results) in real-time, in vivo. The advantages are many: 1) potentially eliminating the need for tissue extraction in cases of benign lesions; 2) analyzing additional physiologic parameters, such as interstitial fluid pressure or tissue oxygenation, which cannot be measured in extracted tissue; 3) better understanding of the tumor microenvironment, which in turn may lead to a better prediction of the course of disease or tumor responsiveness to specific therapies; 4) accurate assessment of tumor margins by discerning the transition from malignant to benign tissue, aiding in 3-dimensional tumor excision; and 5) safer and more efficient surgical operations for a broad range of medical challenges. All of this will lead to improved treatment for patients on earth and in space.

Multi-modality sensing offers a more accurate description of the tissue under study, and is most effective when each of the probe's sensing modalities provides data that independently corroborates a medical indication. For example, hypoxia, high interstitial fluid pressure, and high blood flow are key "independent" parameter values that when found simultaneously gives high confidence that the tumor is malignant. As MEMS and CNT-based microsensors emerge with ever increasing sensitivity and selectivity to chemical and biological markers, the applicability of NSSP technology to other medical challenges will expand quickly.

Animal experiment studies are underway to establish a medical conditions database of normal tissue vs. malignant tumors. Preliminary experimental results are encouraging – unique tissue signatures in high dimensional space have been identified and parameter clustering by tissue type has been confirmed. An intelligent virtual interface has been developed to provide a user-friendly interface to the NSSP technology. A breast cancer detection tool based on this technology has been developed by a commercial company and tested in human clinical trials at the University of California at Davis, School of Medicine.

5. ACKNOWLEDGEMENTS

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