

This work is supported and managed through the NASA Marshall Space Flight Center - SBIR Program. LED-technology developed for NASA plant growth experiments in space shows promise for delivering light deep into tissues of the body to promote wound healing and human tissue growth. We present the results of LED-treatment of cells grown in culture and the effects of LEDs on patients' chronic and acute wounds. LED-technology is also biologically optimal for photodynamic therapy of cancer and we discuss our successes using LEDs in conjunction with light-activated chemotherapeutic drugs.

We have all heard how space technology can benefit us all here on earth; well this is no exception when we look at LED therapy. While the researchers in the field were fine-tuning their devices for pain relief, NASA needed a means to produce light without the added heat produced by incandescent light bulbs for space missions and their plant experiments. NASA settled on (LED's) because of their ability to produce a scattered light of various wavelengths that were of benefit to plants in the confinements of a space vehicle in space flight, while producing no significant increase in thermal heat. They worked, and NASA took the next step. Could LED's help in healing injuries to astronauts while in space flight. One of the major dilemmas for NASA regarding long-term space flight is the well-documented effect of muscle and bone atrophy that occurs to astronauts while in space. In addition it has been shown that injuries that occur while in space tend not to heal until the astronaut is back within the earth's gravity. The LED's that produced near-infrared light used in NASA's research were shown to stimulate the basic energy processes by activating color sensitive chemicals within the cells. DNA synthesis in fibroblasts and muscle cells had been quintupled. The light absorbed by the cells stimulated the metabolism in muscle and bone as well as skin and subcutaneous tissue. What people and animals had felt through utilizing this technology in real life, NASA was proving to be true in the laboratory.

## **LED-ENHANCEMENT OF CELL GROWTH**

Studies on cells exposed to microgravity and hypergravity indicate that human cells need gravity to stimulate growth. As the gravitational force increases or decreases, the cell function responds in a linear fashion. This poses significant health risks for astronauts in long-term space flight. The application of light therapy with the use of NASA LEDs will significantly improve the medical care that is available to astronauts on long-term space missions. NASA LEDs stimulate the basic energy processes in the mitochondria (energy compartments) of each cell, particularly when near-infrared light is used to activate the color sensitive chemicals (chromospheres, cytochrome systems) inside. Optimal LED wavelengths include 680, 730 and 880 nm and their laboratory has improved the healing of wounds in laboratory animals by using both LED light and hyperbaric oxygen. Furthermore, DNA synthesis in fibroblasts and muscle cells has been quintupled using NASA LED light alone, in a single application combining 680, 730 and 880 nm each at 4 Joules per centimeter squared.

Muscle and bone atrophy are well documented in astronauts, and various minor injuries occurring in space have been reported not to heal until landing on Earth. An LED blanket device may be used for the prevention of bone and muscle atrophy in astronauts. The depth of near-infrared light penetration into human tissue has been measured spectroscopically (Chance, et al., 1988). Spectra taken from the wrist flexor muscles in the forearm and muscles in the calf of the leg demonstrate that most of the light photons at wavelengths between 630-800 nm travel 23 cm through the surface tissue and muscle between input and exit at the photon detector. The light is absorbed by mitochondria where it stimulates energy metabolism in muscle and bone, as well as skin and subcutaneous tissue.

Long term space flight, with its many inherent risks, also raises the possibility of astronauts being injured performing their required tasks. The fact that the normal healing process is negatively affected by microgravity requires novel

approaches to improve wound healing and tissue growth in space. NASA LED arrays have already flown on Space Shuttle missions for studies of plant growth and the U.S. Food and Drug Administration (FDA) has approved human trials. The use of light therapy with LEDs can help prevent bone and muscle atrophy as well as increase the rate of wound healing in a microgravity environment, thus reducing the risk of treatable injuries becoming mission catastrophes.

Space flight has provided a laboratory for studying wound healing problems due to microgravity, which mimic traumatic wound healing problems here on earth. Improved wound healing may have multiple applications that benefit civilian medical care, military situations and long-term space flight. Laser light and hyperbaric oxygen have been widely acclaimed to speed wound healing in ischemic, hypoxic wounds. An excellent review of recent human experience with near-infrared light therapy for wound healing was published by Conlan, et al (Conlan, 1996). Lasers provide low energy stimulation of tissues which results in increased cellular activity during wound healing (Beauvoit, 1994, 1995; Eggert, 1993; Karu, 1989; Lubart, 1992, 1997; Salansky, 1998; Whelan, 1999; Yu, 1997) including increased fibroblast proliferation, growth factor synthesis, collagen production and angiogenesis. Lasers, however, have some inherent characteristics that make their use in a clinical setting problematic, such as limitations in wavelength capabilities and beam width. The combined wavelengths of light optimal for wound healing cannot be efficiently produced, and the size of wounds that may be treated by lasers is limited. Light-emitting diodes (LEDs) offer an effective alternative to lasers. These diodes can be made to produce multiple wavelengths, and can be arranged in large, flat arrays allowing treatment of large wounds. Potential benefits to NASA, military, and civilian populations include treatment of serious burns, crush injuries, non-healing fractures, muscle and bone atrophy, traumatic ischemic wounds, radiation tissue damage, compromised skin grafts, and tissue regeneration.

Combat casualty care in Special Operations already have

adopted the NASA LED technology for submarines deployed in training with risk of injury. The USS Salt Lake City is currently underway with an LED Array in the Pacific. Special Operations are characterized by lightly equipped, highly mobile troops entering situations requiring optimal physical conditioning at all times. Wounds are an obvious physical risk during combat operations. Any simple and lightweight equipment that promotes wound healing and musculoskeletal rehabilitation and conditioning has potential merit. NASA LEDs have proven to stimulate wound healing at near-infrared wavelengths of 680, 730 and 880 nm in laboratory animals, and have been approved by the U.S. Food and Drug Administration (FDA) for human trials. The NASA LED arrays are light enough and mobile enough to have already flown on the Space Shuttle numerous times. LED arrays may be used for improved wound healing and treatment of problem wounds as well as speeding the return of deconditioned personnel to full duty performance. Examples include: 1. Promotion of the rate of muscle regeneration after confinement or surgery. 2. Personnel spending long periods of time aboard submarines may use LED arrays to combat muscle atrophy during relative inactivity. 3. LED arrays may be introduced early to speed wound healing in the field. Human trials have begun at the Medical College of Wisconsin, Naval Special Warfare Command, Submarine Squadron ELEVEN and NASA-Marshall Space Flight Center.

## **Wound Healing with NASA LEDs**

EXPERIMENTS USING AN ISCHEMIA ANIMAL MODEL SYSTEM PROVIDE PRE-CLINICAL DATA RELEVANT TO HUMAN HEALING PROBLEMS, CHRONIC NON-HEALING WOUNDS.

## **LED-Wound Healing in Rats**

An ischemic wound is a wound in which there is a lack of oxygen to the wound bed due to an obstruction of arterial

blood flow. Tissue ischemia is a significant cause of impaired wound healing which renders the wound more susceptible to infection, leading to chronic, non-healing wounds. Despite progress in wound healing research, we still have very little understanding of what constitutes a chronic wound, particularly at the molecular level, and have minimal scientific rationale for treatment.

In order to study the effects of NASA LED technology and hyperbaric oxygen therapy (HBO), we developed a model of an ischemic wound in normal Sprague Dawley rats. Two parallel 11-cm incisions were made 2.5 cm apart on the dorsum of the rats leaving the cranial and caudal ends intact. The skin was elevated along the length of the flap and two punch biopsies created the wounds in the center of the flap. A sheet of silicone was placed between the skin and the underlying muscle to act as a barrier to vascular growth, thus increasing the ischemic insult to the wounds. The four groups, each consisting of 15 rats, in this study include: the control (no LED or HBO), HBO only, LED (880 nm) only, and LED and HBO in combination. The HBO was supplied at 2.4 atm for 90 minutes, and the LED was delivered at a fluency of 4J/cm<sup>2</sup> for fourteen consecutive days. A future study will incorporate the combination of three wavelengths (670nm, 728nm, and 880nm) in the treatment groups.

The wounds were traced manually on days 4, 7, 10, and 14. These tracings were subsequently scanned into a computer and the size of the wounds was tracked using Sigma Scan Pro software. Figure 1 depicts the change in wound size over the course of the 14-day experiment. The combination of HBO and LED (880 nm) proves to have the greatest effect in wound healing in terms of this qualitative assessment of wound area. At day 7, wounds of the HBO and LED (880nm) group are 36% smaller than those of the control group. That size discrepancy remains even by day 10. The LED (880nm) alone also showed to speed wound closure. On day 7, the LED (880 nm) treated wounds are 20% smaller than the control wounds. By day 10, the difference between these two groups has dropped to 12%. This is due to the fact that there is a point

when the wounds from all of the groups will be closed. Hence, the early differences are the most important in terms of determining the optimal effects of a given treatment. This can be seen in Figure 1 at day 14 when the points are converging due to the fact that the wounds are healing.

Analysis of the biochemical makeup of the wounds at days 4, 7, and 14 is currently underway. The day 0 time point was determined by evaluating the punch biopsy samples from the original surgery. The levels of basic fibroblast growth factor (FGF-2) and vascular endothelial growth factor (VEGF) were determined using ELISA (enzyme linked immunosorbent assay). The changes in the VEGF concentration throughout the 14-day experiment can be seen in Figure 2. The LED (880 nm) group experiences a VEGF peak at day 4 much like the control group. In contrast, the hyperoxic effect of the HBO suppresses the day 4 peak, and instead, the HBO groups peak at day 7. The synergistic effect of the HBO and LED (880 nm) can be seen at day 4. The VEGF level for the group receiving both treatments is markedly higher at day 4 than the HBO only group. The HBO and LED (880 nm) treated group also experiences the day 7 peak characterized by the HBO treatment. Hence, there is a more uniform rise and fall to the VEGF level in the combined treatment group as opposed to the sudden increases seen in the control, LED only, and HBO only groups. By day 14, the HBO treated groups have dropped closer to the normal level than the LED (880 nm) only or control groups.

The synergistic effects of HBO and LED (880 nm) can be seen easily in Figure 3. The pattern of the changes in basic fibroblast growth factor (FGF-2) concentration is similar to that of the VEGF data. It is clear that the LED (880 nm) day 4 peak is higher than the day 4 peak of the control group. These peaks can be attributed to the hypoxic effect of the tissue ischemia created in the surgery. The hyperoxia of the HBO therapy has a greater effect on suppressing the FGF-2 concentration at day 4 than the VEGF concentration at the same time point. The synergy of the two treatments is evident when looking at the HBO and LED (880 nm) treated group.

The concentration of FGF-2 at day 4 is significantly enhanced by the LED (880 nm) treatment. Whereas, the level would normally drop off by day 7 for a LED-only treated wound, the HBO effect seizes control causing the concentration of FGF-2 to plateau. Hence, an elevated FGF-2 concentration is achieved throughout the greater part of the 14 day treatment with both HBO and LED (880) therapies. Further analysis of the excised wounds will include matrix metalloproteinase 2 and 9 (MMP-2 and MMP-9) determination by ELISA, histological examination, and RNA extraction