MR-Guided Feedback Control of Laser Thermal Therapy

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Introduction

Fiber optic delivery of laser energy makes possible the delivery of large doses of energy to almost any site in the body with relative ease and minimal invasiveness. However, the complicated and highly non-linear way in which light interacts with a turbid and non-homogeneous medium such as tissue makes impossible sufficiently accurate *a priori* prediction of laser damage zones [1]. We have therefore developed a system which uses information derived from temperature sensitive MR images to effect closed-loop feedback control of laser thermal therapy in real-time. The system provides an interactive interface through which the user may regulate laser lesion production and a hardware interface to modulate laser delivery parameters based on temperature feedback data. In this abstract, we report results of preliminary experience with this system.

Methods

We used Xwindows to develop a user interface to hardware and software which provide feedback control of laser heating when interfaced to an MR console. The system uses a network file sharing protocol to interface to the MR console via ethernet and acquire raw data sets as they become available. Images are reconstructed by the Linux workstation and used to generate temperature maps based on calculated phase differences as per the proton resonance frequency (PRF) method [2,3].

Software Interface

In addition to generating "thermal maps", the system uses time-temperature history data to evaluate an Arrhenius rate process damage integral and generate a "damage map" which corresponds to a calculated region of irreversible damage [4]. Feedback control is accomplished by allowing the user to interactively select several target points on a guide image and to create a set of rules which are evaluated by a fuzzy-logic controller in order to drive lesion production based on the temperatures at the target points. Figure-1 is a "screenshot" of the user interface during laser irradiation of rat hind limb muscle *in vivo*.

MR Imaging

Temperature sensitive images were generated using gradient recalled echo (GRE) sequences implemented on a TecMag console interfaced to a 2T 31cm horizontal bore superconducting magnet. Sequences used included a 256x256 sequence which provided images with 300 μm in plane resolution in just under 10 seconds and a 128x128 600 μm resolution sequence which ran in just under 5 seconds. Echo time (TE) was typically between 13 and 21 msec which provided a temperature sensitivity of 4.0 - 6.5 degrees of phase per 1°C rise in temperature.

Laser Interface

Laser lesions were produced by a custom built 5.5 Watt 980 nm fiber coupled diode laser. This laser was equipped with a front panel dial for setting output power and TTL control for output modulation. For a given therapy, maximum power output was first set using calibrated power meter. Subsequent control of laser output power by the computer was effected by pulse width modulation through the TTL line using a DIO board installed in the computer. Laser energy was delivered to the target by a .3 mm diameter diffusing tip fiber with a 200 μm silica core fiber and a 5 mm long diffusing element (CardioFocus, Inc. West Yarmouth, MA).

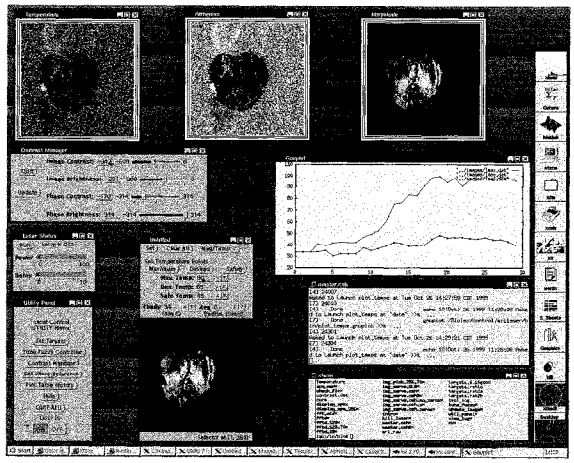

Figure-1: *Screenshot of Laser Control User Interface.* Shown at top (L to R) are images of temperature, estimated damage, and magnitude. Also shown are interactive target selection window, laser status indicator, and user override. Lesion is evolving in the lower left corner of the image.

Results

We have performed preliminary testing of this system both *in vitro* in samples of beef cardiac muscle and *in vivo* in the rat hind limb muscle. *In vitro* lesions were elliptical in shape and feedback control was used to limit the size of the lesion in the radial direction. *In vitro* lesions were produced by placing the fiber subcutaneously on top of the hind limb muscle and limiting either the depth or lateral extent of the lesion. Table-1 summarizes lesion control results for both *in vitro* and *in vivo* lesions.

Table-1*: Lesion Control Results*

Lesion Category	Average Command Lesion Size	Average Actual Lesion Size	% Error
In Vitro Small (n=6)	7.77	7.82	-0.6
In Vitro Large (n=4)	11.90	11.16	-6.3
In Vivo Lateral (n=4)	11.227	11.765	+4.8
In Vivo Depth (n=4)	4.14	4.15	+0.24

Discussion

We have constructed a system for MR-guided closed-loop feedback control of laser lesion production. Preliminary results indicate that temporal, spatial, and thermal resolution of thermal data from MR phase difference images is suitable for effective control of therapy using a relatively low power laser. Improvements in image speed will allow control of faster energy deposition methods.

References

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