Fiber-optic DTG array used for quasi-distributed temperature monitoring in radiofrequency thermal ablation of liver

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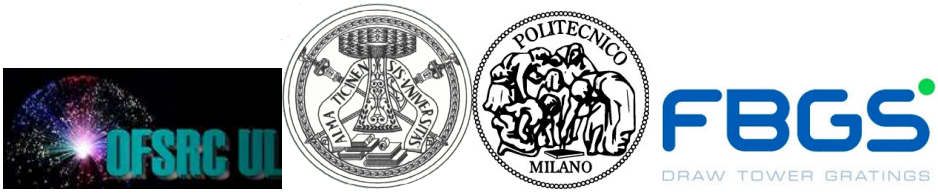


Rationale
Radiofrequency thermal ablation (RFTA) is an emerging treatment for lung, kidney, and hepatic tumors. A miniature electrode with a few mm active length is inserted percutaneously at the point of care, localized at the center of the tumor. A mid-power RF field, input to the ablation electrode, produces a localized high-temperature field that exceeds 120°C at the ablation tip, and with thermal gradient in excess of 3°C/mm. High temperature exposure is cytotoxic for tumor cells: 1 minute exposure at 52°C is a reference for tumor cells mortality condition. In this project, an optical fiber draw-tower Bragg grating (DTG) array has been used to monitor temperature in real-time during several ablation procedures, performed with medical-grade RF equipment on porcine liver phantom. Due to the tensile strength and biocompatibility of the fiber sensor, and the successful penetration through the tissue, the achieved results are exportable to *in-vivo* real-time RFTA monitoring.

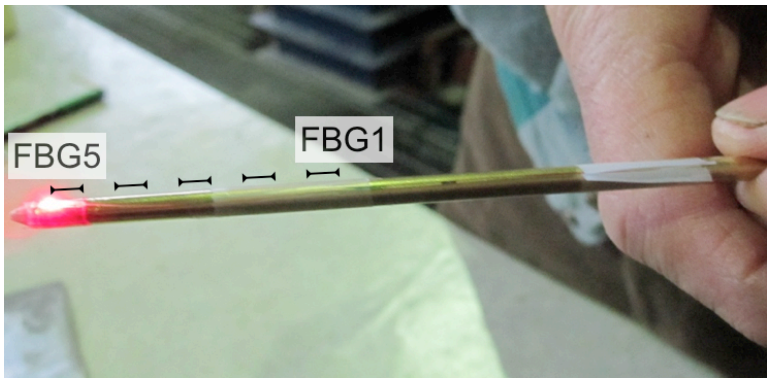
Why RFTA? It provides reduced invasiveness for patients, as it is based on a precutaneous device; it leads to outpatient treatment.

Why liver? The electrical properties of the liver limit the ablation duration to 3-5 minutes, and 2-3 cm diameter, without any additional support. In order to treat mid-to-large tumors (3-5 cm), it is necessary to optimize the RFTA.

Why sensing? Temperature value and persistence are directly correlated to the mortality rate of tumor cells. Measuring temperature at the point of care is a real-time metric of RFTA performance, better than imaging.

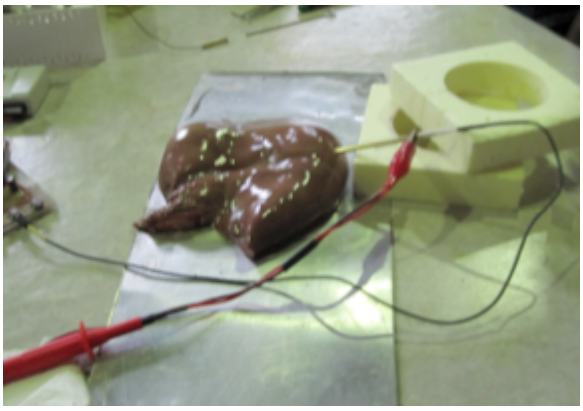
Why DTG? DTGs provide in-line sensing with 1 cm resolution, in a form factor that minimizes invasiveness and does not alter the RFTA pattern. DTGs are also MRI-compatible and do not suffer from hysteresis (as thermocouples). The tensile strength of the fiber can sustain percutaneous insertion without altering sensing performances.

DTG Installation and RFTA Set-up



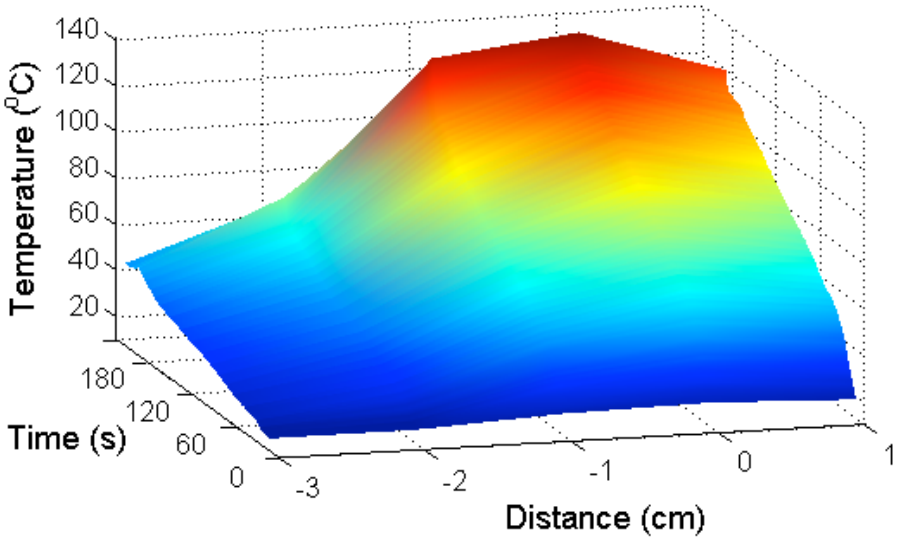
DTG array including 5 sensors, with 1 cm spacing and 0.5 cm active length. Bare fiber with 125 μm thickness, with no additional protection, patched on a 4-mm ablation device, with 1 cm active length.

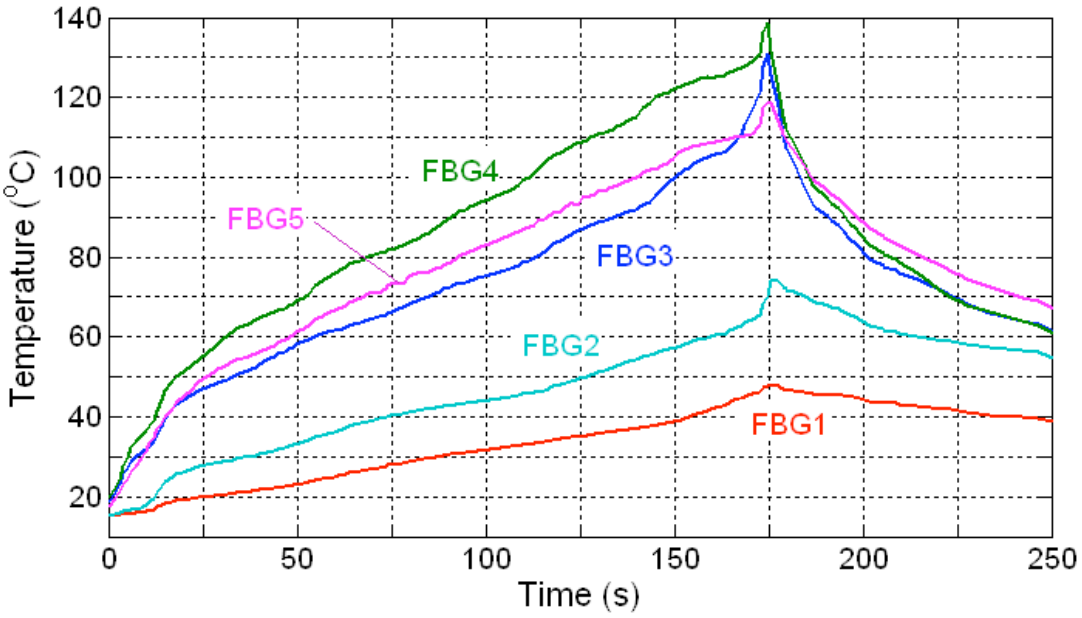
The RFTA ablation device mounting DTG array sustains insertion into porcine liver phantom (which best matches the biological and electrical properties of human liver). 20 W RF power is applied by a medical-grade RF generator at 480 kHz, which mounts an impedance meter sensor. RF power is disconnected when impedance exceeds 300 Ω.



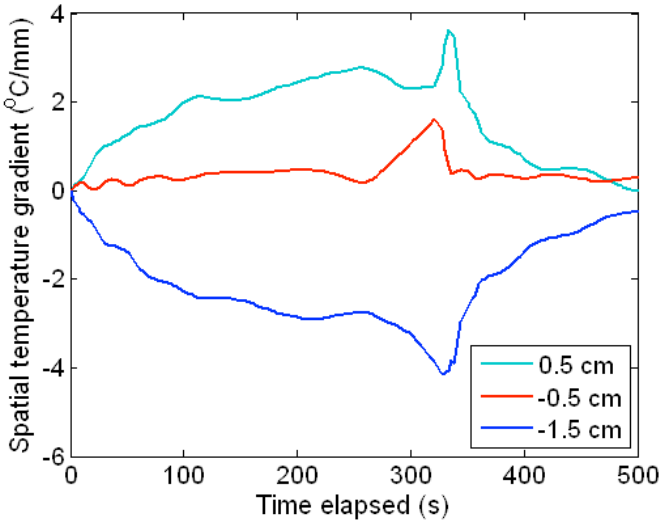
Results

The setup records temperature with 1 Hz rate in 5 points at different distances from the ablation device tip; FBG4 is positioned at the ablation tip, FBG3 and FBG5 at 1 cm distance, FBG2 at 2 cm distance and FBG1 at 3 cm distance. The chart reports the temperature distribution along the ablation horizontal axis as a function of distance from the ablation tip and time elapsed from the ablation start, showing the steep thermal gradient in both time and space.

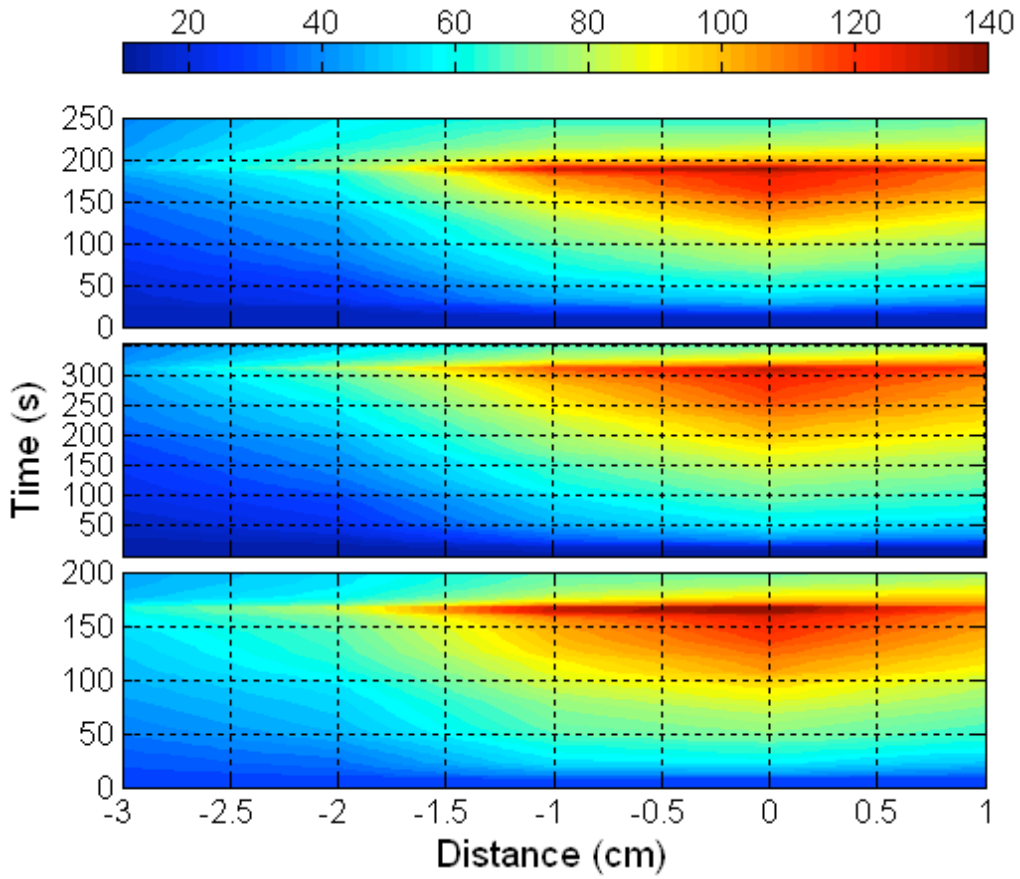




The figure above shows a RF ablation, with duration 174 s, reporting the temperature readout on each FBG. The DTG array clearly visualizes the behavior of RFTA ablation: at the ablation point (FBG4), temperature experiences an immediate linear rise (1.7°C/s) until 55°C, reducing its gradient to 0.85°C/s after 45 s. When temperature exceeds 100°C, the water constituent of the biological tissue transitions from liquid to vapor phase, rapidly increasing the tissue impedance and leading to RFTA sudden stop. A quick temperature rise is observed in proximity of the peak. Temperature recorded at 1 cm distance is lower throughout the whole procedure, with a visible rise in proximity of the RF generator disconnection. It is possible to observe that when the RF generator is disconnected, the high-temperature field “propagates” with a transient along distance, about 3s from FBG4 to FBG1. These effects, together with the neat temperature peak, have been observed in every ablation recorded with DTGs; due to hysteresis, slower response, and poor multiplexing capability, thermocouples do not detect with such precision these phenomena.



Additional data pertain to the analysis of the spatial temperature gradient, between two sensing points; the chart reports the value for three distances for a slow (320 s) ablation. The absolute gradient observed diverges fro the initial value to over 2°C/mm on the positive side and -3°C/mm on the negative side. At the ablation point, a maximum gradient of -4.05°C/mm is observed.



The temperature distribution along the longitudinal axis is reported for three different RFTA procedures, on the same 20 W RF power and on similar porcine tissues; the color-map reports temperature in °C. Peak temperatures of 138.5°C, 133.1°C, and 131.6°C have been observed. The three charts provide a quantitative determination of the exposure of each portion of the tissue to cytotoxic temperatures, quantifying the exposure time. In the first chart, in particular, we observe that for negative distance the 60°C threshold, which guarantees a high mortality rate is achieved for a distance inferior to 2.4 cm from the ablation peak. A similar value (2.5 cm) is observed for the second RFTA, while the third ablation, despite being the shortest, guarantees an exposure to 58°C or higher all the way through the RFTA needle.

Conclusions

The project aims at understanding the phenomena related to RFTA throughout biophysical sensors operating in real-time. The quasi-distributed temperature measurement, with a sensor that can sustain insertion in the tissue similarly to a trocar, is a key asset. *Ex-vivo* measurements show increased measurement accuracy over thermocouples, and pave the road for *in-vivo* application for real-time temperature detection. The team foresees the realization of a RFTA device installing optical fiber sensors, with temperature data driving the RFTA procedure in a closed-feedback way (*smart-ablation* concept).