Fibre probe for tumour laser thermotherapy with integrated temperature measuring capabilities

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Y. Liu, R. Gassino, A. Braglia, A. Vallan, and G. Perrone

The development and preliminary characterization of a novel fibre probe for laser thermotherapy of solid tumours are presented. The probe introduces two innovative features: the tailoring of the laser irradiation pattern to adapt it also for larger tumour applications, and the all-optical real time evaluation of the induced temperature increase. These features are simultaneously obtained by integrating in a single capillary tube a laser delivery fibre with properly micro-structured tip surface together with some fibre Bragg gratings. Preliminary validation examples in human liver phantoms have demonstrated the viability of the proposed approach for the development of a whole set of new probes for laser ablation in medical applications.

Introduction: Cancer, one of the most common and fatal diseases, had over 14 million of new incidences in 2012, a figure that is expected to almost double, rising to 24 million, by 2030 [1]. To date, despite the progresses of clinical cures, the most effective treatment for malignant solid tumours is still surgical resection. For cases where this approach is not practical (e.g. due to unsuitable lesion location, nodule number, other concomitant diseases, or insufficient organ function), minimally invasive techniques, like percutaneous thermal ablations, have proved to be effective radical treatment alternatives [2]. These techniques induce the necrosis of tumour cells by raising the target volume at cytotoxic temperature; among them, laser-induced thermotherapy (LITT), also often referred to as laser ablation (LA), is advantageous over the more assessed microwave (MWA) or radiofrequency (RFA) ablations for its full compatibility with magnetic-resonance imaging (MRI), lower costs and simplified implementation. In particular, with guidance of MRI, LITT allows more accurate and safe ablation of tumours located near high-risk sites [3]. However, despite the excellent performance so far demonstrated [4], LITT is still hampered mainly by the limited shape of the area in which temperature is raised and the necessity of strict temperature control within this area. Indeed, whereas the treated area should be large enough to cover the entire tumour with certain safety margins, the temperature has to be sufficiently high to kill tumour cells (generally, this means higher than about 50°C), but not too high to induce excessive mechanical stress due to water vaporization, to decrease the affected area due to tissue carbonization, or – even worse – to induce severe major complications after treatment.

To overcome these limitations, we have devised an all-optical LITT probe that combines the delivery and suitable diffusion of high power laser ablation beams with real-time temperature measurement capability. In the following, the concept of this probe, its design and the system to use it are described; then, preliminary validation tests conducted in human liver phantom, such as suitable jelly material and porcine liver, are presented to assess the probe functionality in conditions mimicking actual application conditions.

Probe Development: The probe is made by one large core silicate fibre used for the delivery of the ablation laser beam, surrounded by some standard telecom fibres with inscribed Bragg gratings (FBGs) in their core acting as temperature sensors. The bundle is inserted into a silicate capillary tube, as sketched in Fig. 1, possibly together with other dummy fibres used to improve the mechanical stability.

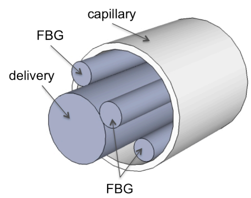


Fig. 1 S*ketch of the laser ablation probe with fibre Bragg grating sensors for real-time temperature monitoring (picture not in scale).*

To preserve biocompatibility, no glues are used and the fibres are kept in position by collapsing the capillary. For the same reason the probe front end-facet is sealed by splicing a larger silicate fibre and then cleaving it very short.

In order to properly shape the beam diffusion pattern, the lateral surface of the laser delivery fibre tip is micro-structured using a CO_2 laser. This introduces a key innovative feature because the high power laser beam can be distributed more uniformly over the target tumour area, avoiding localized overheating as it may occur in standard fibre deliveries where the laser irradiation is from the tip end-facet only. Moreover, with this approach it is possible to adapt the irradiation pattern to different tumour geometries and sizes in a reproducible way by tailoring the pitch, size and number of micro holes made by the CO_2 laser beam.

Another key feature of the probe is the capability of real time temperature monitoring. The effect of the tissue exposure to the laser beam is usually hard to predict because of the variability of its optical and thermal properties due to local chemical composition differences, vascularization, and extent of coagulation. All this implies that optimal LITT requires an accurate control of the temperature, and possibly not in a single point only. Traditional approaches rely mainly on thermocouples for their being cost-effective [5]; however, since their metallic conductors absorb the laser beam, they introduce artefacts in the measured data due to local increase of temperature, with a subsequent overestimation of the actual tissue temperature. To avoid these perturbations, in the proposed probe the temperature measurement is through FBGs positioned around the delivery fibre, moreover with a longitudinal offsets between one another to allow sampling the temperature distribution in different points along the central axis of the target area. Extensive comparisons through thermographic images between thermocouples and fibre Bragg grating based temperature sensors have demonstrated that, being all-fibre devices, the perturbation introduced by the FBGs can be considered negligible. The temperature spatial resolution is strongly limited by the grating length – shorter grating, even with lower reflectivity peak are preferred – but the devised arrangement based on spatial longitudinal stacking has proved leading to quasi-distributed measurements with results that can be considered acceptable for most practical LITT applications. The interrogation of the temperature sensors makes use of the scheme in Fig. 2. The gratings are spectrally multiplexed through a beam splitter (BS) and fed by a broadband fibre-pigtailed SLED source; then the reflected spectra are routed via a circulator to a commercial portable spectrometer (FBGA) having a wavelength resolution of about 100 pm. Using standard gratings with a temperature sensitivity of about 10 pm/°C, the resulting temperature resolution of about 10°C is clearly insufficient; however, it can be improved to about 0.1°C by spectral fitting and other signal processing techniques [6]. A 10W laser diode (LD) at a wavelength of 915 nm has been chosen as the laser source for the tumour ablation demonstration for the combination of the penetration depth at this wavelength and the very favourable cost-per-watt.

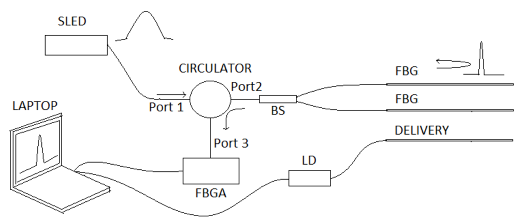


Fig. 2 S*ketch of the probe connection with evidenced the temperature interrogation setup.*

Prior to the demonstration of its effectiveness in an actual ex-vivo porcine liver, the probe has been characterized in terms laser irradiation pattern and temperature monitoring capabilities using a liver phantom made with dye-loaded agar gel. This choice allows performing the measurements in a much more reproducible environment, thus with the possibility to compare different probe solutions. The concentration of the agar and the dye in the phantom are chosen to have thermal conductivity and optical absorption similar to actual liver tissue [7-8].

Experiment Results: In the preliminary tests, probes made with 400 µm delivery fibres with various micro structures have been sandwiched between two 5-mm thick agar gel slices. This emulates an actual working condition but with the possibility of measuring the induced temperature distribution close to the probe with a thermographic camera by quickly removing the upper jelly disc at the end of each laser exposure period [9]. Fig. 3 shows the measured temperature distributions for two probes with different patterning of the fibre tip. Exposure time and laser power have been limited for not rising the temperature above 50°C, a temperature at which the agar phantom starts changing its properties and thus it is no longer representative of the actual liver behaviour. The probes used in these tests included two 15-mm FBGs, one aligned with the laser diffusing micro structures and the other 2cm away. The obtained thermographic images were in good agreement with the readings from the FBGs, with a maximum difference of less than 2.5°C, which can be due to both the averaging effect over the active length of FBG (about 15 mm in the current case), and the slightly different measurement conditions between the thermal camera and the FBGs.

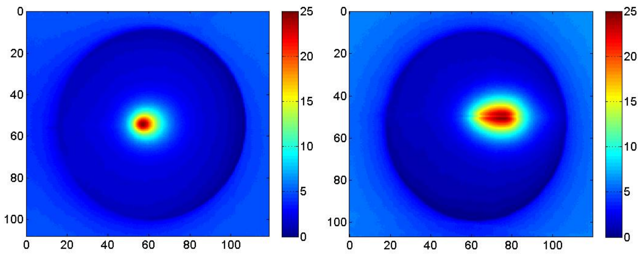
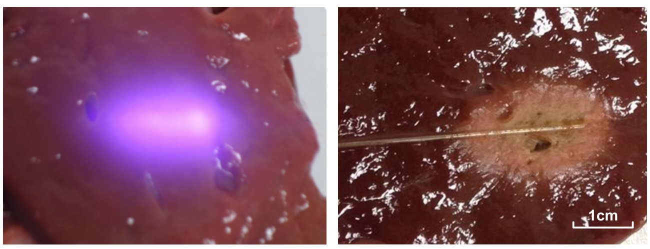


Fig. 3 *Thermal images of the agar phantom with two probes having different irradiation patterns; ticks are in millimetre and colour bars represent temperature increments over room temperature (about 20 °C); the laser power is 2W.*

Fig. 4 reports two images taken during tests conducted in porcine liver with the same laser tip in Fig. 3-right, which allows treating an area of about 25×20 mm. The shape and size of the beam diffusion area as measured from the VIS-NIR and thermal cameras in these cases coincide well with those obtained in the agar phantom, proving therefore also the effectiveness of the dye-loaded agar to mimic an actual liver.



a *b*

Fig. 4 *Photographs of porcine liver undergoing and after laser ablation using the proposed probe.*
a Picture through the liver evidencing the irradiation shape of the probe; *b* coagulation induced by applying 4W of laser power for about 10 minutes.

For comparison with the agar phantom case, first a test at 2W of laser power has been conducted. The measured temperature is reported in Fig. 5-left, which shows that the maximum temperature reached in the porcine liver is consistent with that in the agar phantom, providing another indirect validation of the phantom. Then, a second test at 4W has been conducted in another location of the liver. The measured temperature from the two gratings is reported in Fig. 5-right. It should be noted that the site of FBG1 (i.e. closer to the irradiation area) starts to coagulate from ~140s, while that of the FBG2 after ~440s. This shows that by comparing the readings from the temperature sensors it will be possible in future developments to optimize the laser ablation treatment.

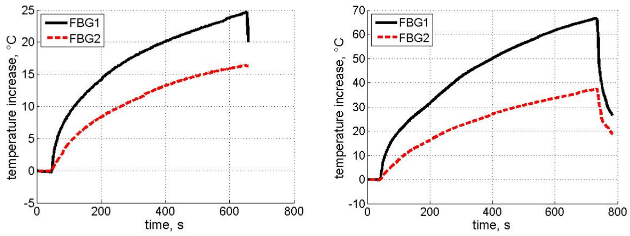


Fig. 5 *Temperature evolution recorded by FBGs inside porcine liver during 2W (left) and 4W (right) of laser ablating. FBG1 is aligned with the area of maximum laser irradiation and FBG2 is 2cm away.*

Conclusion: An all-fibre probe for the simultaneous delivery of a high power laser beam and the measurement of the induced temperature rise in tumour ablation applications has been developed. Characterizations carried out comparing the readings from the probe with thermographic images in working conditions similar to actual operative conditions have demonstrated the effectiveness of the proposed solution and encourage further developments toward clinical applications.

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