Journal of Innovative Optical Health Sciences
Vol. 8, No. 5 (2015) 1550018 (6 pages)

DOI: 10.1142/S1793545815500182

Carbon-coated magnetic particles increase tissue temperatures after laser irradiation

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Received 4 August 2014
Accepted 4 November 2014
Published 2 December 2014

Purpose: This work focused on the investigation the hyperthermia performance of the carbon-coated magnetic particles (CCMPs) in laser-induced hyperthermia. Materials and methods: We prepared CCMPs using the organic carbonization method, and then characterized them with transmission electron microscopy (TEM), ultraviolet-visible (UV-Vis) spectrophotometry, vibrating sample magnetometer (VSM) and X-ray diffraction (XRD). In order to evaluate their performance in hyperthermia, the CCMPs were tested in laser-induced thermal therapy (LITT) experiments, in which we employed a fully distributed fiber Bragg grating (FBG) sensor to profile the tissue's dynamic temperature change under laser irradiation in real time. Results: The sizes of prepared CCMPs were about several micrometers, and the LITT results show that the tissue injected with the CCMPs absorbed more laser energy, and its temperature increased faster than the contrast tissue without CCMPs. Conclusions: The CCMPs may be of great help in hyperthermia applications.

Keywords: Carbon-coated magnetic particles; hyperthermia; laser.

1. Introduction

Magnetic nanoparticles have been widely used to improve the quality of magnetic resonance imaging, drug delivery, cell separation and hyperthermia applications.[1–3] Many kinds of magnetic nanoparticles have been prepared, such as ultra-small superparamagnetism iron oxide particles and carbon-coated magnetic nanoparticles.[4–7]

Hyperthermia is a therapeutic procedure that raises the temperature of a region of the body

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affected by cancer. The elevated temperature can be produced by various methods, such as microwave, ultrasound, laser or a magnetic field.[8] Hyperthermia combined with radiation treatment, chemotherapy or photodynamic therapy may improve the efficacy of cancer therapies.[9–13] Some studies found that injecting nanoparticles into the tumor also improved the cancer treatment.[14,15] Nanoparticles, such as gold nanoparticles or gold nanorods, have been shown to strongly increase the absorption of laser light, which helps target the heat to the tumor cells.[16,17] Some studies have demonstrated that iron oxide magnetic nanoparticles and carbon nanotubes can effectively mediate hyperthermia.[18–21] Carbon-coated magnetic particles (CCMPs) also absorb a significant amount of laser light, and they therefore may mediate hyperthermia as well as magnetic particles, or carbon nanotubes.

Fiber Bragg grating (FBG) are widely used for specific applications in aeronautics, the automotive industry, structure monitoring in civil engineering and undersea oil exploration for the measurement of various parameters such as strain, force, pressure, displacement, temperature, humidity and radiation dose.[22] Recently, FBG has been used in biomedical application such as biomechanics[22,23] and hyperthermia.[24,25] FBG could measure multi-point temperature, and this would be helpful for the temperature detection and control to avoid the normal cells from being damaged during cancer hyperthermia. In this paper, we prepared the CCMPs and investigated their performance in mediating laser-induced hyperthermia by using the FBG as a fully distributed temperature sensor to measure the temperature distribution in tissues.

2. Materials and Methods

2.1. *Preparing CCMPs*

We used the organic carbonization method[26] to prepare CCMPs. Iron (III) nitrate nonahydrate ($Fe(NO_3)_3 \cdot 9H_2O$) (0.8 g), poly(vinyl alcohol) (PVA) (2.1 g) and poly(vinyl pyrrolidone) (0.2 g) were dissolved into 40 mL water. The solution was heated for about 4 h at 100°C to evaporate the water. Then the solutes were heated to above 400°C with nitrogen for several minutes, producing the CCMPs.

2.2. *Characterizing CCMPs*

Drops of diluted CCMPs solutions were deposited on carbon films supported by copper grids and then air-dried in a ventilation cabinet. A JEM-200CX (JEOL, Japan) transmission electron microscope (TEM) was used to study the particle morphology. The CCMPs powder were characterized by X-ray diffraction (XRD) on a D/MAX-2200 X-ray diffractometer (Rigaku, Japan). Magnetic characterization of CCMPs was carried out using a vibrating sample magnetometer (7407, LakeShore, USA) at room temperature with maximum applied field of 2.3 T. The ultraviolet-visible (UV-Vis) adsorption spectra of CCMPs dispersed in deionized water were collected on a UV-2102PCS UV-Vis spectrophotometer.

2.3. *Cell and tissue experiments*

Human hepatoma cells (SMMC 7721) were cultured in Dulbecco's modified Eagle medium (DMEM) supplemented with 10% heat-inactivated fetal bovine serum (FBS). Cells were maintained under

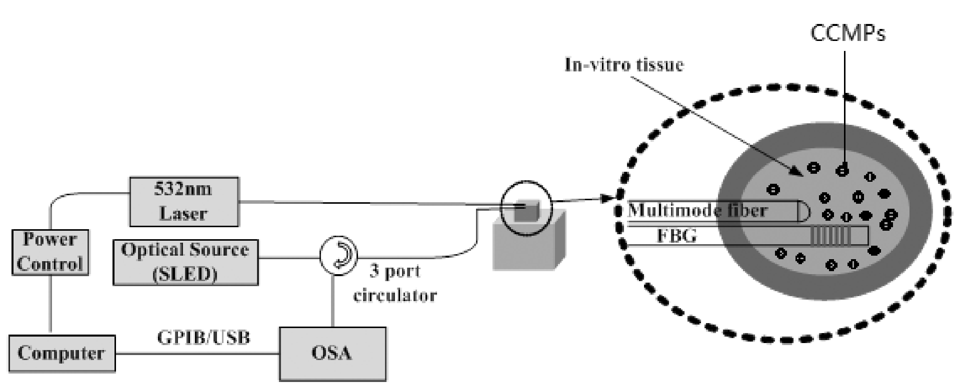


Fig. 1. Schematic of the tissue hyperthermia experiment.

standard cell culture conditions at 37°C with 5% CO_2. Cells dissociation was processed using 0.25% Trypsin-EDTA, and cells were mixed with the CCMPs when exposed to the laser. The muscle tissue used in this experiment came from pork bought from the supermarket. CCMPs were injected about 10 mm into the muscle tissue.

The solid-state laser (MLL-H-532, Changchun New Industries Optoelectronics Technology Co., Ltd.) with a total power of 900 mW at the wavelength of 532 nm was used in the photothermal treatment. The 532-nm laser was transmitted to the tissue through the multimode fiber, where the output power from the multimode fiber coupled to the sample was about 261 mW. Then, the tissues and the nanoparticles absorbed the laser energy, and their temperature rose subsequently. The temperature detection device with the distributed FBG sensor was designed in our laboratory, and it can detect the temperature dynamically at roughly 8 s intervals, as shown in Fig. 1.

3. Results

3.1. *Characterizing the CCMPs*

The XRD, magnetization curve and TEM image of the CCMPs were measured and analyzed. The results are shown in Figs. 2–4.

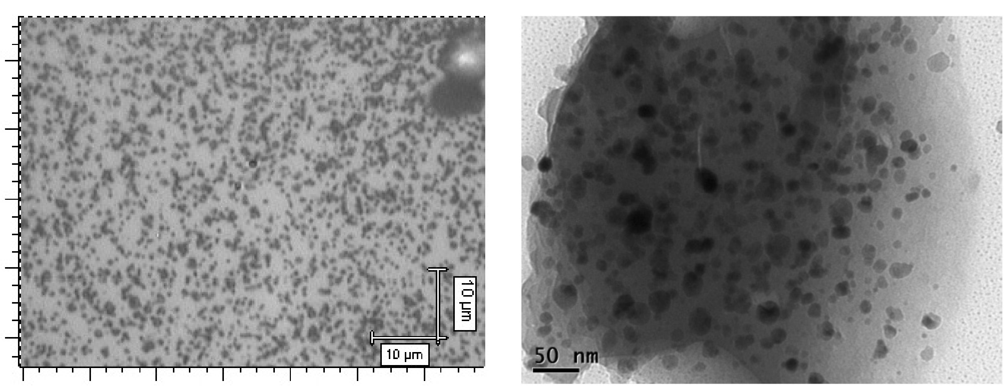
The magnetic nanoparticles were dispersed in the carbon, and the mean size of the magnetic nanoparticles was about 15 nm. The average size of the CCMPs was about several micrometers. The XRD spectrum of the CCMPs shows that the magnetic nanoparticles were Fe_3O_4, and the estimated crystallite size was about 9 nm using X-rays data by Jade software. The PVA blocked the crystal development process of Fe_3O_4, and the carbon coated on the Fe_3O_4 weakened the peak of the XRD spectra. The saturation magnetization was about 5.27 emu/g, the carbon may also affect the magnetism of the magnetic particles.

The UV-Vis absorption spectra of CCMP water solutions were shown in Fig. 5, whereby wavelength scanning was performed from 200 nm to 800 nm. Deionized water was used to construct the baseline for the measurement. The results from the UV-Vis absorption spectra imply that CCMPs can absorb about 60% of the laser energy in a 10 mg/mL CCMPs–water solution.

3.2. *Cell and tissue experiments*

Cells mixed with CCMPs produced higher temperatures of laser irradiation than cells without CCMPs [Fig. 6(a)]. Without cells, the CCMPs solution absorbed more laser power than water (without CCMPs) at the same conditions [Fig. 6(b)]. These results show that CCMPs can absorb laser energy and increase temperatures, so they may be beneficial for laser-induced hyperthermia.

The temperature distribution was measured in the pork muscle tissue under laser-induced hyperthermia (Fig. 7). The highest temperature achieved in the water-injected tissue was about 50°C, whereas that of the CCMP-injected tissue was 60°C. The results show that the tissue injected with CCMPs absorbed more laser energy, and its temperature increased faster than the contrast tissue without CCMPs.



(a) (b)

Fig. 2. Images of the CCMPs. (a) Optical images of the CCMPs; (b) TEM images of the CCMPs.

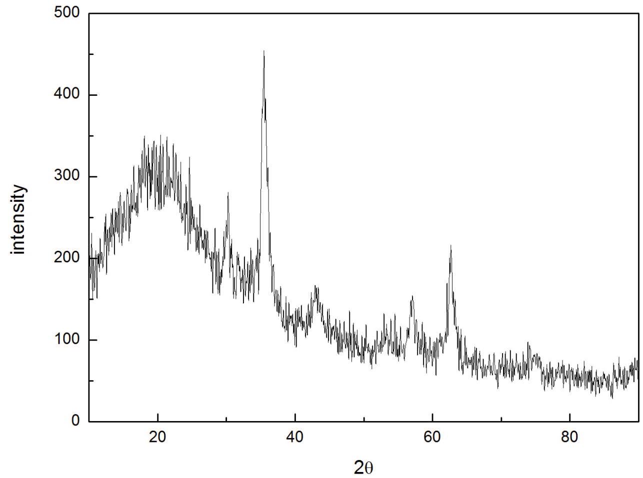


Fig. 3. Powder X-ray diffraction pattern of the CCMPs.

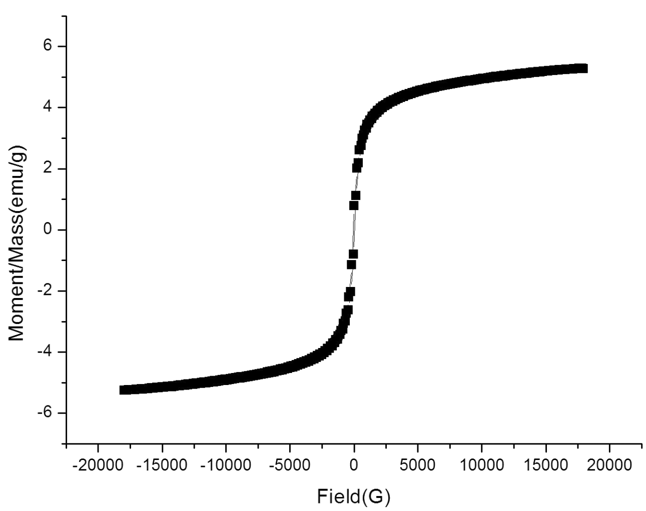


Fig. 4. Magnetization curves of the CCMPs.

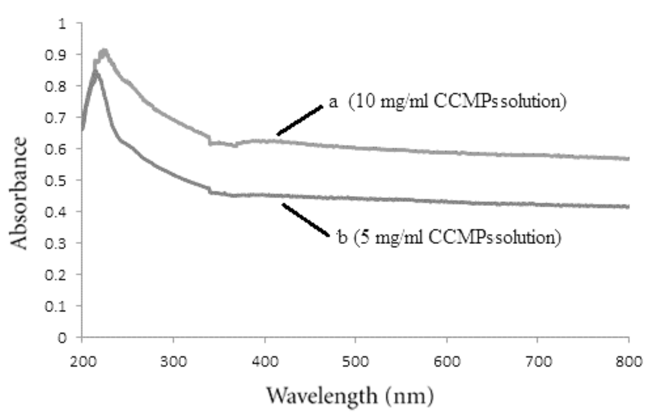


Fig. 5. UV-Vis absorption spectra of CCMPs. (a) 10 mg/mL CCMPs-water solution; (b) 5 mg/mL CCMPs-water solution.

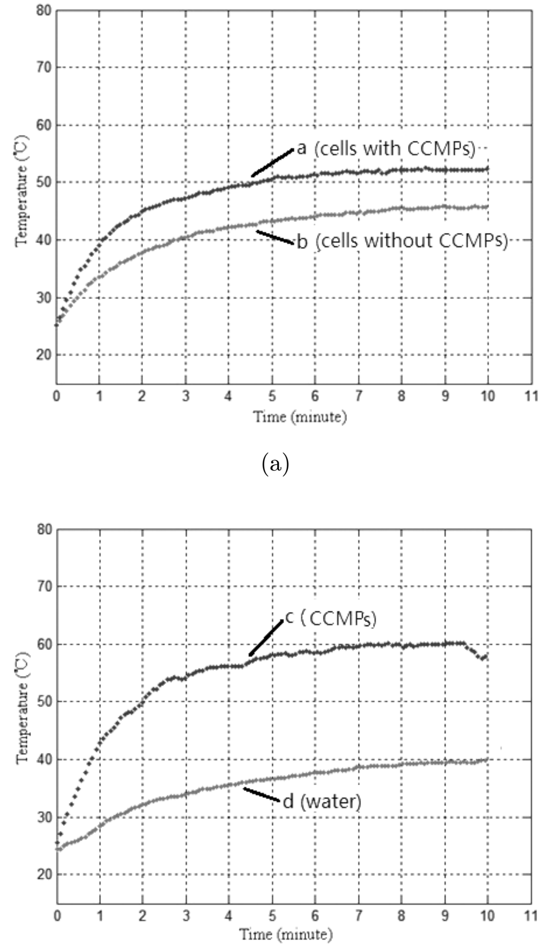


Fig. 6. Temperature curves with time as laser irradiation to cells and water. (a) Line a shows the temperature curve of a cell solution mixed with CCMPs (0.2 mL cell + 0.1 mL 0.03 g/mL CCMPs); Line b shows the temperature curve of a cell-only solution (0.2 mL cell + 0.1 mL water). (b) Line c shows the temperature curve of a CCMPs solution (0.3 mL 0.03 g/mL CCMPs); Line d shows the temperature curve of water alone (0.3 mL water).

4. Discussion

The magnetic iron oxide nanoparticles have good biocompatibility and are already used with hyperthermia treatments clinically and in research.[27,28] Consequently, magnetic particles were selected for photoabsorption in laser-induced hyperthermia. Carbon has also been used previously as a photoabsorption material.[18] Therefore, CCMPs were studied as a photoabsorption material for laser-induced hyperthermia in this paper.

The CCMPs were prepared and tested with laser irradiation. We found that water or cell solutions

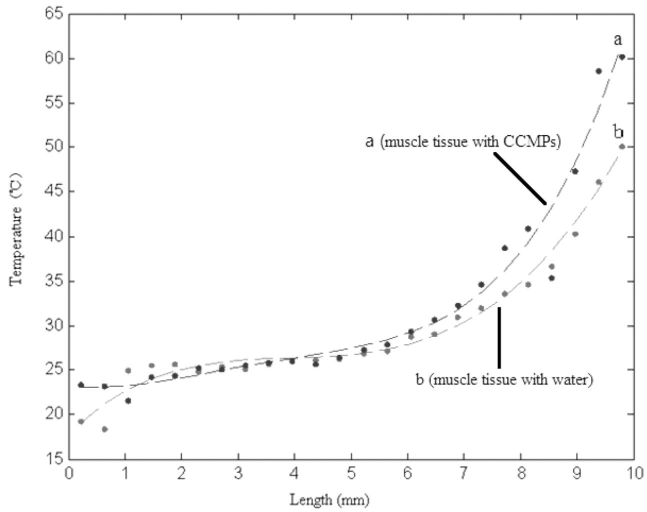


Fig. 7. Temperature profile of the muscle tissue after laser irradiation. (a) muscle tissue with 0.2 mL of a 0.03 g/mL CCMPs solution; (b) Muscle tissue with 0.2 mL water (without CCMPs).

that contained CCMPs absorbed more laser power than water or cell solutions without CCMPs. In addition, CCMPs allowed for higher muscle tissue temperatures than non-CCMP-containing tissue because the particles helped to focus the heat to a specific location. Therefore, when CCMPs are injected into cancerous cells, their "focusing" capability may help prevent healthy tissue from being destroyed when laser-induced hyperthermia is performed in cancer therapy.

Our future work will focus on hyperthermia therapy experiments using CCMPs in a cancerous mouse model. Because CCMPs can absorb laser energy, they may be helpful in cancer hyperthermia therapy.

Acknowledgments

This work is supported by the Natural Science Foundation of China (NSFC) (61027015, 61177088, 61107076) and the National Program on Key Basic Research Project (973 Program, 2012CB723405). We would like to thank Dr. Bo Lu from the Laboratory for Microstructures for helping us analyze the XRD and magnetism data.

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