Journal of Innovative Optical Health Sciences
Vol. 7, No. 1 (2014) 1350053 (7 pages)

DOI: 10.1142/S1793545813500533



# REAL-TIME ASSESSMENT OF MICROWAVE ABLATION EFFICACY BY NIR SPECTROSCOPIC TECHNIQUE

JINZHE ZHAO*, ZHIYU QIAN*,‡,**, JIA LIU†,§,**,
YA XU* and JIALI WU*
*Department of Biomedical Engineering
Nanjing University of Aeronautics and Astronautics
Nanjing, P. R. China

†The Affiliated Tumor Hospital of Xiangya
Medical School of Central South University/Hunan
Provincial Tumor Hospital, Changsha, P. R. China
‡zhiyu@nuaa.edu.cn
§liujia121212@163.com

Received 18 June 2013
Accepted 12 September 2013
Published 30 October 2013

Microwave ablation (MWA) status monitoring in real time plays a key role in assessment of therapeutic effectiveness. As a novel real-time assessment method, near infrared spectroscopy (NIRs) was used to evaluate the ablation efficacy. MWA experiments were carried out on *in vitro* porcine livers. An optical measurement system for biological tissue is developed by our lab to monitor reduced scattering coefficient ($\mu_s'$) at 690 nm of the coagulation zones. It is noted that $\mu_s'$ of liver tissue, which increases as the liver tissue being ablated, is clearly related with the coagulation status. $\mu_s'$ of normal tissue and coagulated tissue is 3–5 and 17–19 $cm^{-1}$, respectively. Continuous changes of $\mu_s'$ demonstrate that optical parameter can be used as an efficacy evaluation factor because it essentially indicates the degree of thermal damage. Compared with temperature, optical parameter is more sensitive and accurate, which is promising for real-time therapeutic efficacy assessment in MWA.

*Keywords*: Near infrared spectroscopy; reduced scattering coefficient; therapeutic efficacy.

## 1. Introduction

Microwave ablation (MWA), a new thermal ablation technique, has been regarded as a safe and efficient treatment for many types of tumors. Advantages of MWA include high ablation temperature, large ablation volume, benefits of being minimally invasive

**Corresponding authors.

and ability to use multiple applicators.[1–3] Due to the low morbidity and mortality rates, MWA has become one of the most popular thermal ablation method for treatment of hepatic malignancy.[4,5]

MWA is usually performed percutaneously with guidance of ultrasonography (US), computed tomography (CT) or magnetic resonance imaging (MRI).[4,6–9] US is more convenient and can be used in real time during the entire treatment process to judge the size of ablation zone by measuring the expanding hyperechoic area. However, thermal probes are needed for monitoring tissue temperature at tumor margin in order to achieve accurate real-time efficacy assessment.[7]

Thermal damage process is a rate process that exponentially depends on temperature and linearly depends on exposure time, which can be quantified using an Arrhenius integral with two experimentally derived coefficients: frequency factor $A$ and activation energy $E_a$.[10–12] Because temperature and exposure time both contribute to thermal damage degree, the ablation status must be determined by temperature history instead of transient temperature. This brings difficulties to judge ablation effect when the temperature is maintained relatively low.

Several studies have revealed that thermal damage significantly affects optical properties of liver tissue. A decrease in the absorption coefficient ($\mu_a$) and anisotropy factor ($g$) and an increase in the scattering coefficient ($\mu_s$) occurred during the heating procedure, which were due to the protein denaturation.[13–16] Dynamic changes of fluorescence and reflectance spectrum have also been reported to correlate with thermal damage in liver tissue and results from radio frequency ablation demonstrated that spectroscopy method is promising for evaluation of thermal ablation efficacy.[17–19] However, such studies on MWA are sparse and no evaluation factors or standards are available.

This paper aims to present a new method for real-time assessment of ablation efficacy. During MWA, reflectance spectrum and reduced scattering coefficient ($\mu_s'$) of liver tissue were measured by an optical parameter measurement system which was previously reported.[20,21] The reduced scattering coefficient ($\mu_s'$) was calculated through empirical equations using the slope of the spectrum within 700–850 nm. These equations were deduced from extensive experiments. Different concentrations of intralipid and phantom were utilized for simulation in these experiments and correlation between $\mu_s'$ and slope value were fitted. Comparing the $\mu_s'$ value measured by this measurement system to that of Oximeter, $\mu_s'$ on 690 nm was more accurate and had an error of $2\,\text{cm}^{-1}$.

## 2. Materials and Methods

### 2.1. *MWA system*

KY-2000 MWA system (Kangyou Medical Instruments, Nanjing, China) consists of microwave generator, flexible coaxial cable, water-cooled microwave antenna and microwave output control unit. The microwave generator is capable of producing 1–100 W of microwave power at irradiation frequency of 2.45 GHz. The microwave antenna is 15 cm in length and 1.9 cm in diameter. It is coated with Teflon material to prevent adhesion from the tissue induced by high temperature during the ablation. A peristaltic pump enables circulating saline water to cool the antenna continuously.

### 2.2. *Tissue parameter measurement system*

The real-time parameter measurement system consists of a halogen light source (HL-2000, Ocean optics), a USB fiber optic spectrometer (USB2000, Ocean optics) and a homemade optic-thermal probe (see Fig. 1). USB2000 was used to measure reflectance spectrum ranging from 340 to 1020 nm. The optic-thermal probe includes a bifurcated optical fiber and a thermo sensor that is located in the end of the probe. The diameter of each fiber is 200 $\mu$m; resolution of the thermo sensor is 0.2°C. A computer program is used to monitor the changes of the parameters and optical coefficient $\mu_s'$ is calculated in real time.

### 2.3. *Optical parameter measurement of ablated tissue*

Fresh porcine livers were obtained from local slaughterhouse. Experiments were carried out at a room temperature of 20°C. Before ablation, the livers were kept under 20°C for 30 min and then laid in a homemade positioning template.

Microwave antenna was inserted into the liver at least for 10 cm to ensure that the entire ablation area would be within the liver parenchyma. For this part of experiments and following, the dose of 70 W of microwave power and 300–600 s of emission time

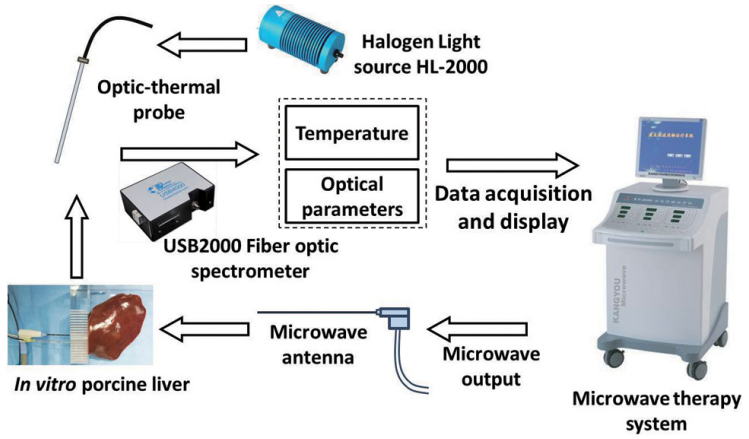



Fig. 1. System setup for MWA and real-time data acquisition.

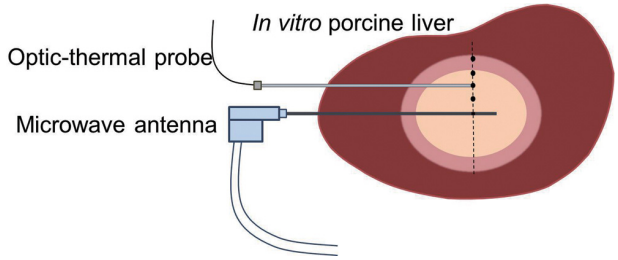



Fig. 2. Measurements of optical parameters and temperature during ablation.

was determined empirically as it generates a relatively large ablation zone with small charring area.

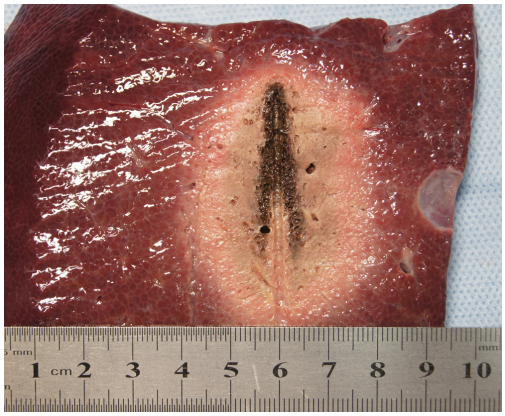
Six ablations (divided into 2 groups) were performed, under 70 W for 300 and 600 s, respectively. Ablated livers were then cut along the antenna axis to expose the coagulated zones. On the liver section, optical parameter was measured every 3 mm along both short axis and long axis so as to completely measure the whole surface. A stainless steel ruler was used to measure the distances and the error which was 1 mm.

### 2.4. *Monitoring of optical parameter and temperature in real time*

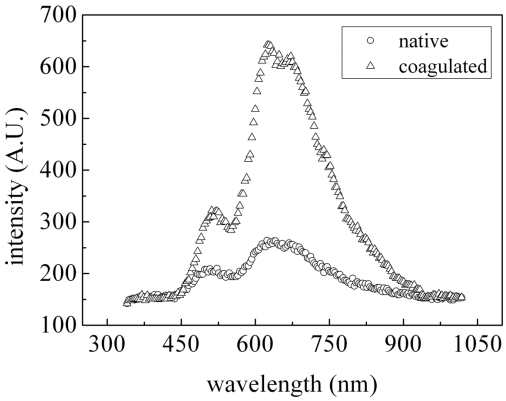
Microwave antenna and probe were both inserted into liver tissue through a positioning template. Distances between the probe and antenna were set as 10, 15 and 20 mm, respectively (see Fig. 2). About 70 W of microwave power and 600 s of emission time were employed. Six ablations (two ablations for each distance) were carried out. The probe was inserted into the livers paralleled to the microwave antenna.

## 3. Results

Coagulation zones are all generally ellipsoidal. Figure 3(a) shows one gross specimen after ablation. Three zones can be distinguished as charring zone




(a)




(b)

Fig. 3. (a) Ablated liver section and (b) measured spectrum of native and coagulated tissue.

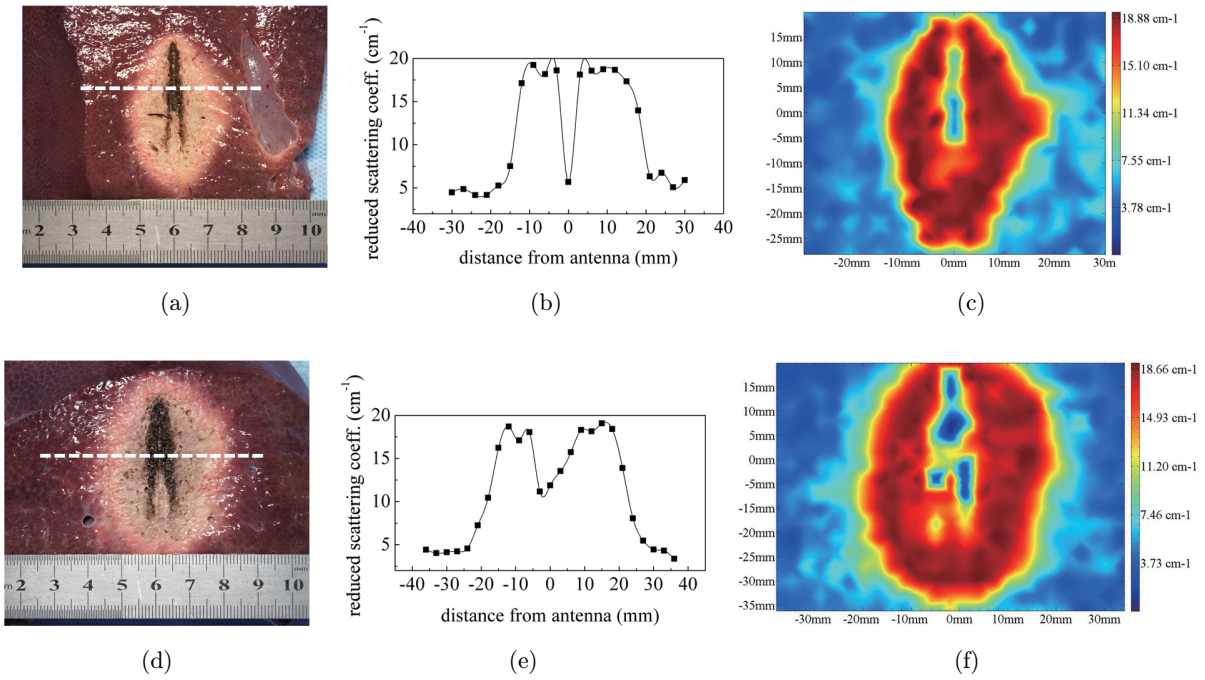



Fig. 4. Liver specimens ablated after 300 s (a) and 600 s (d) ablation with both 70 W microwave output power. (b) and (e) the $\mu_s'$ changes along the white line in (a) and (d). (c) and (f) the distribution of $\mu_s'$ along the whole ablated area surface of (a) and (d).

(black arrow shape in the center), coagulation zone (light yellow in color) and congestion zone (red thin hyperemic band around the coagulation zone).

Reflectance spectrum obtained from the coagulated tissue and native tissue is in Fig. 3(b). Significant increase of the spectrum intensity was observed from 460 to 920 nm. Peaks at 515 and 630 nm and valley at 550 nm were sharper. $\mu_s'$ from the spectrum of coagulated tissue and native tissue is 3–5 and 17–19 $cm^{-1}$, respectively.

$\mu_s'$ was measured on the section of the ablated tissue. Figure 4 shows the distribution of $\mu_s'$ along the white line. Moreover, all the values of $\mu_s'$ are shown in Figs. 4(e) and 4(f) using pseudo color with interpolation.

During the ablation, $\mu_s'$ and temperature were measured in real time. The variation of $\mu_s'$ and temperature at the sites 10, 15 and 20 mm away from the antenna are shown in Fig. 5, respectively. Same microwave dose, 70 W of microwave power and 600 s of microwave output were used. For all three measuring sites, $\mu_s'$ increases as temperature rises and after coagulation $\mu_s'$ reached a plateau. When microwave output is shut off at 600 s, temperature decreases and $\mu_s'$ remains stable.

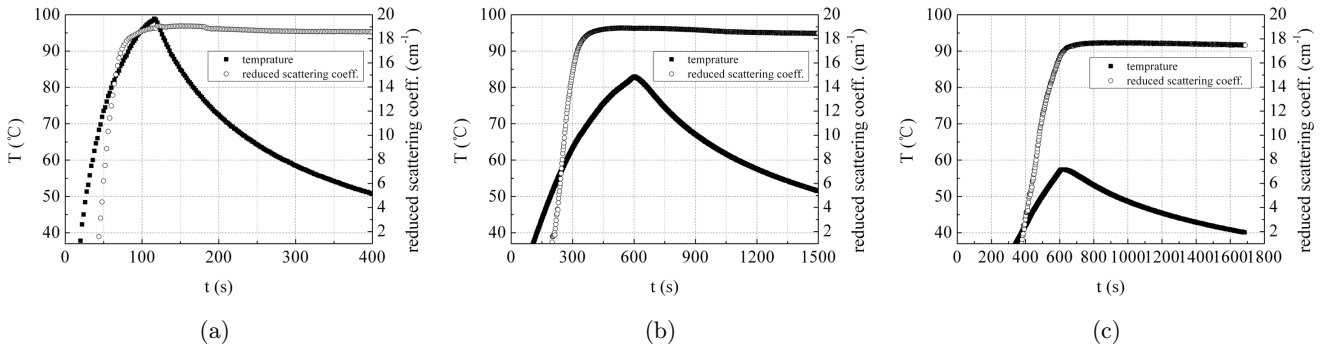



Fig. 5. The time dependences of temperature and $\mu_s'$ during ablation. Microwave output for (a) 113 s, probe at 10 mm away from antenna; (b) 600 s, probe at 15 mm away from antenna; (c) 600 s, probe at 20 mm away from antenna.

## 4. Discussion

Though MWA has been employed for clinical liver tumor therapy for many years, there are still many problems that need to be solved. Several studies used a series of microwave dose to carry out *in vitro* and *in vivo* MWA experiments.[22–26] Different size of ablation zones were obtained in these experiments, which provided reference for clinicians. But such ablation experiments were mostly carried out in livers, the information from other organs was rare. In addition, the diversity among patients and different properties of employed antennas further complicates the prediction for therapeutic results. Therefore, intraoperative monitoring of ablation efficacy is highly necessary.

Thermal probes are employed to detect real-time temperature changes during ablation by locating then at tumor margin or adjacent to important organs. A temperature of 60°C or 54°C maintained for 3 min is considered as a coagulation threshold.[27,28] Yet if a relatively low temperature (under 54°C) occurs at the tumor margin, it will be difficult to judge the end time for microwave output.

As shown in Fig. 4, red area depicts the region where $\mu_s'$ is larger than 15 $cm^{-1}$, which implies fully that coagulation has happened. Also, the shape of red area well meets the coagulation zone in the corresponding picture. Low value in the center corresponds to the charring zone and transition from red to blue corresponds to the congestion zone. It is worth noting that $\mu_s'$ changes rapidly within the narrow congestion band which divides the native and coagulated regions. This implies that $\mu_s'$ is very sensitive to the thermal damage degree of liver tissue.

A similar microwave treatment dose (70 W of power, 600 s of emission time) was used in the real time parameter monitoring experiments in order to reveal continuous changes of $\mu_s'$ and temperatures at three different distances away from the antenna during the process.

The results show an identical trend for both $\mu_s'$ and temperature. In Fig. 5(a), both $\mu_s'$ and temperature are rising rapidly as 10 mm is a close distance from the antenna. Temperature reaches 99°C at 113 s and then the microwave output is shut off automatically. Under such a high temperature, liver tissue easily becomes coagulated, which implies that $\mu_s'$ reaches a plateau in a short time. For the 15-mm site, highest temperature reaches 83°C at 600 s while $\mu_s'$ reach the plateau. However, after the temperature reaches a maximum of 57.4°C at 20 mm site, $\mu_s'$ still shows a slightly increase. This means coagulation is much slower and has a delay at a long distance site from the antenna and the coagulation zone is still growing even when microwave output is shut off.

As $\mu_s'$ shows a simple increasing trend during ablation and has corresponding distribution with the coagulation status, a certain threshold of $\mu_s'$ can be found between 5 and 17 $cm^{-1}$ as an evaluation factor, which confirms that the real-time efficacy assessment method is feasible.

## 5. Conclusion

A new method for the MWA efficacy assessment is proposed in this paper. Reflectance spectrum differs from native and coagulated tissue, the calculated $\mu_s'$ clearly corresponds to the tissue thermal degree. In the future, more attention will be paid to the detailed pathological analysis and determination of $\mu_s'$ threshold. Consequently, a real time MWA efficacy assessment system will be perfectly established.

## Acknowledgment

This work is a part of the project 61378092 supported by NSFC and also funded by the construction project "Microwave Ablation Clinical Application Exploration in the Comprehensive Treatment of Cancer", based on the research platform of the Affiliated Tumor Hospital of Xiangya Medical College, Central South University. The authors are also grateful for the Funding of Jiangsu Innovation Program for Graduate Education (No.CXLX13_147), the Fundamental Research Funds for the Central Universities.

## References

1. C. J. Simon, D. E. Dupuy, W. W. Mayo-Smith, "Microwave ablation: Principles and applications," *Radiographics* **25**, S69–S83 (2005).
2. G. Carrafiello, D. Lagana, M. Mangini, F. Fontana, G. Dionigi, L. Boni, F. Rovera, S. Cuffari, C. Fugazzola, Microwave tumors ablation: Principles, clinical applications and review of preliminary experiences," *Int. J. Surg.* **6**, S65–S69 (2008).

3. C. Jones, S. A. Badger, G. Ellis, "The role of microwave ablation in the management of hepatic colorectal metastases," *Surgeon* **9**, 33–37 (2011).
4. P. Liang, J. Yu, X. L. Yu, X. H. Wang, Q. Wei, S. Y. Yu, H. X. Li, H. T. Sun, Z. X. Zhang, H. C. Liu, Z. G. Cheng, Z. Y. Han, "Percutaneous cooled-tip microwave ablation under ultrasound guidance for primary liver cancer: A multicentre analysis of 1363 treatment-naive lesions in 1007 patients in China," *Gut* **61**, 1100–1101 (2012).
5. S. Qiu-Jie, H. Zhi-Yu, N. Xiao-Xia, S. Wen-Yuan, S. Yuan-Yuan, H. Liu, L. Xin, L. Ping, "Feasible temperature of percutaneous microwave ablation of dog liver abutting the bowel," *Int. J. Hyperthermia* **27**, 124–131 (2011).
6. W. He, X. D. Hu, D. F. Wu, L. Guo, L. Z. Zhang, D. Y. Xiang, B. Ning, "Ultrasonography-guided percutaneous microwave ablation of peripheral lung cancer," *Clin. Imaging* **30**, 234–241 (2006).
7. P. Liang, Y. Wang, "Microwave ablation of hepatocellular carcinoma," *Oncology* **72**, 124–131 (2007).
8. F. Liu, X. Yu, P. Liang, Z. Cheng, Z. Han, B. Dong, "Contrast-enhanced ultrasound-guided microwave ablation for hepatocellular carcinoma inconspicuous on conventional ultrasound," *Int. J. Hyperthermia* **27**, 555–562 (2011).
9. X. Yu, F. Liu, P. Liang, A. D. Era, Z. Cheng, Z. Han, "Microwave ablation assisted by a computerised tomography-ultrasonography fusion imaging system for liver lesions: An ex vivo experimental study," *Int. J. Hyperthermia* **27**, 172–179 (2011).
10. F. C. Henriques, Jr., "Studies of thermal injury; the predictability and the significance of thermally induced rate processes leading to irreversible epidermal injury," *Arch. Pathol. (Chic.)* **43**, 489–502 (1947).
11. R. Agah, J. A. Pearce, A. J. Welch, M. Motamedi, "Rate process model for arterial tissue thermal damage: Implications on vessel photocoagulation," *Lasers Surg. Med.* **15**, 176–184 (1994).
12. D. Zhu, Q. M. Luo, G. M. Zhu, W. Liu, "Kinetic thermal response and damage in laser coagulation of tissue," *Laser Surg. Med.* **31**, 313–321 (2002).
13. C. T. Germer, A. Roggan, J. P. Ritz, C. Isbert, D. Albrecht, G. Muller, H. J. Buhr, "Optical properties of native and coagulated human liver tissue and liver metastases in the near infrared range," *Lasers Surg. Med.* **23**, 194–203 (1998).
14. J. P. Ritz, A. Roggan, C. T. Germer, C. Isbert, G. Muller, H. J. Buhr, "Continuous changes in the optical properties of liver tissue during laser-induced interstitial thermotherapy," *Lasers Surg. Med.* **28**, 307–312 (2001).
15. J. P. Ritz, A. Roggan, C. Isbert, G. Muller, H. J. Buhr, C. T. Germer, "Optical properties of native and coagulated porcine liver tissue between 400 and 2400 nm," *Laser Surg. Med.* **29**, 205–212 (2001).
16. D. Zhu, Q. M. Luo, J. S. Yu, S. Q. Zeng, Y. Ruan, "The coagulation process of biological tissue measured by light scattering," *P. Soc. Photo-Opt. Ins.* **3863**, 407–411 (1999).
17. W. C. Lin, C. Buttemere, A. Mahadevan-Jansen, "Effect of thermal damage on the in vitro optical and fluorescence characteristics of liver tissues," *IEEE J. Sel. Top. Quantum Electron.* **9**, 162–170 (2003).
18. C. D. Anderson, W. C. Lin, C. R. Buttemere, M. K. Washington, A. Mahadevan-Jansen, J. Pierce, I. B. Nicoud, C. W. Pinson, R. S. Chari, "Real-time spectroscopic assessment of thermal damage: Implications for radiofrequency ablation," *J. Gastrointest Surg.* **8**, 660–669 (2004).
19. C. R. Buttemere, R. S. Chari, C. D. Anderson, M. K. Washington, A. Mahadevan-Jansen, W. C. Lin, "In vivo assessment of thermal damage in the liver using optical spectroscopy," *J. Biomed. Opt.* **9**, 1018–1027 (2004).
20. L. Dai, Z. Qian, K. Li, T. Yang, H. Wang, "In vivo detection of reduced scattering coefficient of C6 glioma in rat brain tissue by near-infrared spectroscopy," *J. Biomed. Opt.* **13**, 044003 (2008).
21. J. Xie, Z. Qian, T. Yang, W. Li, G. Hu, "Minimally invasive assessment of the effect of mannitol and hypertonic saline therapy on traumatic brain edema using measurements of reduced scattering coefficient (mus')," *Appl. Opt.* **49**, 5407–5414 (2010).
22. Z. G. Cheng, Q. J. Xiao, Y. Wang, Y. Y. Sun, T. Lu, P. Liang, "915 MHz microwave ablation with implanted internal cooled-shaft antenna: Initial experimental study in in vivo porcine livers," *Eur. J. Radiol.* **79**, 131–135 (2011).
23. F. Y. Liu, X. L. Yu, P. Liang, Y. Wang, P. Zhou, J. Yu, "Comparison of percutaneous 915 MHz microwave ablation and 2450 MHz microwave ablation in large hepatocellular carcinoma," *Int. J. Hyperthermia* **26**, 448–455 (2010).
24. Y. Wang, Y. Sun, L. Feng, Y. Gao, X. Ni, P. Liang, "Internally cooled antenna for microwave ablation: Results in ex vivo and in vivo porcine livers," *Eur. J. Radiol.* **67**, 357–361 (2008).
25. C. L. Brace, P. F. Laeseke, L. A. Sampson, T. M. Frey, D. W. van der Weide, F. T. Lee, Jr., "Microwave ablation with multiple simultaneously powered small-gauge triaxial antennas: Results from an in vivo swine liver model," *Radiology.* **244**, 151–156 (2007).
26. W. Shi, P. Liang, Q. Zhu, X. Yu, Q. Shao, T. Lu, Y. Wang, B. Dong, "Microwave ablation: Results with double 915 MHz antennae in ex vivo bovine livers," *Eur. J. Radiol.* **79**, 214–217 (2011).

27. B. Dong, P. Liang, X. Yu, L. Su, D. Yu, Z. Cheng, J. Zhang, "Percutaneous sonographically guided microwave coagulation therapy for hepatocellular carcinoma: Results in 234 patients," *AJR Am. J. Roentgenol.* **180**, 1547–1555 (2003).

28. P. Liang, B. Dong, X. Yu, D. Yu, Y. Wang, L. Feng, Q. Xiao, "Prognostic factors for survival in patients with hepatocellular carcinoma after percutaneous microwave ablation," *Radiology* **235**, 299–307 (2005).