33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Modeling the Internal Pressure Dependence of Thermal Conductivity and in vitro Temperature Measurement for Lung RFA

Nozomu Yamazaki, Hiroki Watanabe, Masatoshi Seki, Takeharu Hoshi,
Yo kobayashi, *Member, IEEE*, Tomoyuki Miyashita, Masakatsu G. Fujie, *Senior Member*, *IEEE*

Abstract— **Radio frequency ablation (RFA) for lung cancer has increasingly been used over the past few years because RFA is minimally invasive treatment for patients. As a feature of RFA for the lung cancer, lung has the air having low thermal conductivity. Therefore, RFA for lung has the advantage that only the tumor is coagulated because heating area is confined to the immediate vicinity of the heating point. However, it is difficult for operators to control the precise formation of coagulation zones due to inadequate imaging modalities. We propose a method using numerical simulation to analyze the temperature distribution of the organ in order to overcome the current deficiencies. Creating an accurate thermophysical model was a challenging problem because of the complexities of the thermophysical properties of the organ. In this work, as the processes in the development of ablation simulator, measurement of the pressure dependence of lung thermal conductivity and in vitro estimation of the temperature distribution during RFA is presented.**

I. Introduction

A. Radio frequency ablation (RFA) for cancers

Radio frequency ablation (RFA) is an important method for treating tumors and has increasingly been used over the past few years [1]-[3]. RFA involves an electrode being percutaneously introduced into the tumor and RF energy being applied, whereupon the temperature of the tissue rises due to the ionic agitation generated by the microwaves at 470 kHz. Tissue coagulation occurs as a result of protein denaturation when the tissue around the electrode reaches a temperature of around 60°C. Subsequently, moisture evaporation occurs and the tumors become completely necrotic at 70-80°C. This percutaneous procedure, which has proven to be effective and safe, also has the advantage of being minimally invasive, meaning lower-impact operations and shorter hospital stays.

Manuscript received April 15, 2011. This work was supported in part by Global COE (Centers of Excellence) Program "Global Robot Academia", in part by Grant Scientific Research 22360108, 21700513, from MEXT (Ministry of Education, Culture, Sports, Science and Technology of Japan), High-Tech Research Center Project from MEXT, and in part by a Waseda University Grant for Special Research Project (2010B-177).

N. Yamazaki, H. Watanabe, M. Seki, Members of the Graduate School of Science and Engineering, Waseda University, Japan. (59-309, 3-4-1, Okubo, Shinjuku Ward, Tokyo, Japan, e-mail: nozomu0626@akane.waseda.jp, tel: +81-3-5286-3412, fax: +81-3-5291-8269).

T. Hoshi, Y. Kobayashi, T. Miyashita, M. G. Fujie, Members of the Faculty of Science and Engineering, is with the Graduate School of Science and Engineering, Waseda University, Japan.

B. RFA for lung cancer

In recent years, the effectiveness of RFA has been reported for liver cancer and breast cancer, and as a consequence RFA is now beginning to be applied in lung cancer. The RFA procedure for lung cancer is to percutaneously puncture the tumor with the RF electrode. Subsequently, the operator checks an ablation region and the relative positions of the tumor and RF electrode using X-ray CT. Finally, the radio wave is turned on.

A characteristic of RFA for lungs is that these organs contain abundant air. Air is low in thermal conductivity. Therefore, the internal air focuses the RF energy from an electrode needle onto a limited region. Thus the lung is more suitable for cauterization than breasts, livers, bones..

C. Practical shortcomings of RFA for lung cancer

On the other hand, precise cauterization of lung tumors is very difficult because the presence of pneumothorax and air inside the lung greatly affects the thermal distribution. In fact, the excessive ablation or non-ablation of tumors has been reported in lung RFA treatment [4]-[6]. In the case of the lung as compared with other organs such as the liver, the actual region of ablation may not coincide with the original region that was targeted by the operator.

The objective of this study is to develop a precise ablation simulator based on acccurate thermophysical model of lung to support RFA treatment of lung cancer. The ablation simulator will show the following information as visual information for the operator [7]:*1)* Optimized RF energy to cauterize the lung tumor*, 2)* Appreciation of the ablation region and ablation time*, 3)* Heat conduction of the normal tissue adjacent to the cancer.

D. The thermophysical model of lung

In order to construct an accurate ablation simulator, it is necessary to use a reliable thermophysical model which has an accurate database of the thermophysical properties of the organ such as thermal conductivity and specific heat. However, creating an accurate thermophysical model was a challenging problem because of the complexities of the thermophysical properties of the organ. One of the complexities is that the thermal conductivity of lung changes with internal the pressure of lung. The thermal conductivity is included in the bio heat equation (1) that is required to calculate the tissue temperature around the tumor.

$$\rho c \frac{\partial \theta}{\partial t} = \lambda \nabla^2 \theta + \sigma |E|^2 - \rho \rho_b c_b F(\theta - \theta_b) + Q_m \qquad (1)$$

where ρ is the density of the organ [kg/m^3], c its heat capacity [J/kgK], θ its temperature in °C, λ its thermal conductivity [W/mK], σ its electrical conductivity [S/m], E its electrical field [V/m], ρ_b the density of blood, c_b the heat capacity of blood, F the blood perfusion coefficient of the organ [m^3/kgs], θ_b the blood temperature and Q_m the metabolic heat source term of the organ [W/m^3].

If the thermal conductivity of lung changes according to the internal pressure, due to air flow into the lung, it is required to change the thermal conductivity λ in Eq.(1) according to the internal pressure of the lung when predicting the ablation area using Eq.(1). However, it is not revealed the change tendency of the thermal conductivity of the lungs depending on the internal pressure. Therefore, it is necessary to validate how the thermal conductivity of lung changes with the internal pressure quantitatively to construct an accurate ablation simulator for lung RFA [8].

The novelty of this study is to measure and model the internal pressure dependence of lung based on the quantitative the experiments and constructs the precise ablation simulator for lung RFA reflecting the internal pressure dependence of thermal conductivity. In this paper, we measured the thermal conductivity of the lung as changing the internal pressure and carried out the in vitro experiment to validate the effect of internal pressure on the temperature distribution during RFA

This report is organized as follows: Section II presents the experiment to obatain the internal pressure dependence of thermal conductivity of a hog lung. Section III displays the measurement of the temperature distribution when changing the internal pressure in vitro using the RF generator. Finally, Section V presents our conclusions and plans for future work.

II. THERMAL CONDUCTIVITY OF LUNG

Firstly, we measure and model the internal pressure dependence of thermal conductivity of a hog lung using an internal pressure control device and thermal conductivity measurement device.

A. Principle

In general, two main categories of methods are used to obtain the thermal conductivity of any materials. One category involves unsteady methods, and the other category is the steady methods. Using steady methods, samples need to be cylindrical or disc shaped. On the other hand, using unsteady methods, the shape of samples is not limited. With this in mind, we chose an unsteady method for measuring the thermal conductivity of a lung due to the fact that soft lung tissue is difficult to shape into cylindrical or disc samples. In some unsteady methods, specifically we used the unsteady hot wire method because it is possible to measure the thermal conductivity only by inserting the wire into the tissue. This method involves obtaining thermal conductivity by sensing the temporal temperature change of a heated thin wire that is inserted into the sample. The thermal conductivity of hog lung is calculated, based on a general heat transfer equation, by sensing the rate of increase in the temperature of the wire. In this method, the rate of increase in the temperature of the thin wire is low when the thermal conductivity of the sample is high, because the heat generated by the wire is quickly dissipated into the sample. In contrast, the rate of increase in the temperature of the thin wire is high when the thermal conductivity of the sample is low, because the heat generated by the wire is dissipated into the sample slowly.

B. Method

Figure 1 shows the experimental equipment (Kyoto electronics manufacturing, QTM-500). The equipment consisted of a needle-type sensing unit and a main calculation unit. The needle-type sensing unit consisted of a thin wire for heating the sample and thermocouples for measuring the temperature change of the wire (Fig. 2). In RFA treatment, the ablation is carried out only at the distal portion of the lung because of the limitation of the depth RF needle can reaches. Therefore, we measured the thermal conductivity at the singular portion (Fig. 3). In addition, in order to measure the internal pressure dependence of the thermal conductivity, we developed a pressure control system.The pressure control system can supply air to the lung with a flow rate of 3.0 L/min which is the same rate of human breath motion. Using this system, lung internal pressure can be controlled to become higher than atmospheric pressure. We measured the thermal conductivity as changing the internal pressure from 0 to 3.0 kPa using this pressure control system. The minimum value of 0 kPa was simulate collapse lung, and the maximum value of 3.0 kPa was determined based on the fact that 3.0 kPa is the maximum pressure achieved during human breathing. Moreover, the measurement was carried out using two individual left hog lungs.

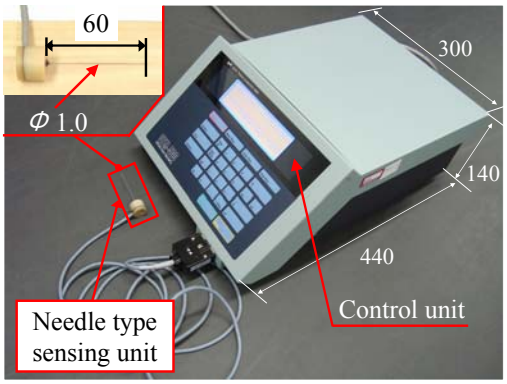

Fig.1: Unsteady hot wire method machine

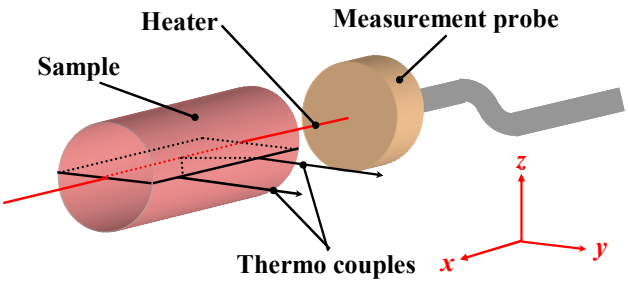

Fig.2: Sample setting using the unsteady hot wire method

C. Result

Figure 4 shows the hog lung at each pressure. And Fig. 5 shows the measured thermal conductivity of hog lung obtained from two trials, with the average value of the latter. We found that the thermal conductivity of the lung decreased linearly within the pressure range 0 to 2.0 kPa, and was constant within the range 2.0 to 3.0 kPa. Via the experimental data, the relationship between pressure P_{lung} kPa and thermal conductivity λ_{Air} W/mK was modeled as equations (1) and (2):

$$\lambda_{Air} = aP_{lung} + b \quad (P_{lung} < 2.0\text{kPa}) \tag{1}$$

$$\lambda_{Air} = c \quad (P_{lung} > 2.0\text{kPa}) \tag{2}$$

Where a is -8.80×10^{-2}, b is 1.80×10^{-1}, c is 0.125.
According to Fig. 4, it was confirmed that the thermal conductivity with in the range from 2.0 kPa to 3.0 kPa was less than about 40 % of its value at 0 kPa.

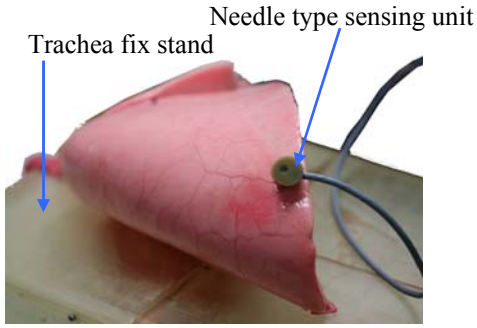

Fig.3: Experimental setup

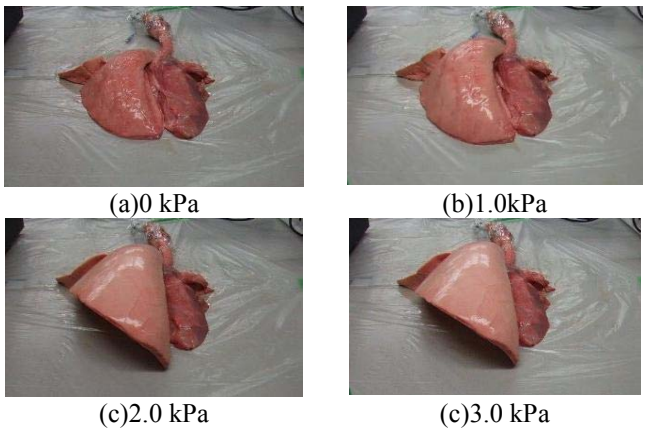

Fig. 4: lung expanded for each lung internal pressure

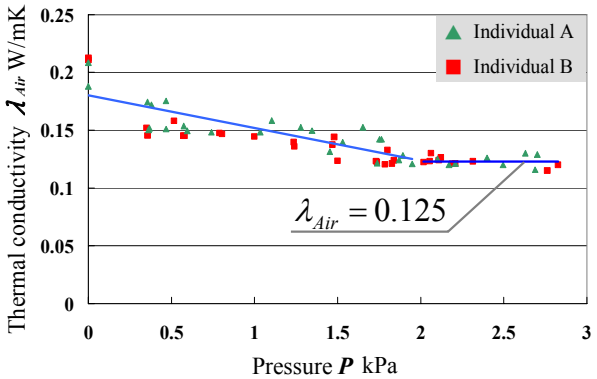

Fig. 5: Internal pressure dependence on lung thermal conductivity

D. Discussion

As a result of the experiment, the thermal conductivity of hog lung declined linearly within the pressure range of 0 to 2.0 kPa and converged within the range 2.0 to 3.0 kPa. It is expected that alveoli continue to expand with increasing lung internal pressure from 0 to 2.0 kPa. However, alveoli do not expand at pressures greater than 2.0 kPa. As a consequence, thermal conductivity converged at 2.0 kPa. It is also understood from Fig. 4. Fig. 4 shows that the lung exhibited a large expansion from 0 to 2.0 kPa, but its size was almost the same from 2 to 3.0 kPa. It is well known that the existence ratio of the air volume relative to the lung parenchyma volume increased with rising lung internal pressure [9]-[10]. Therefore, it is suggested that the reason why the lung thermal conductivity remained constant from 2.0 to 3.0 kPa is because the ex istence ratio of the air and the lung parenchyma volume did not change from 2.0 to 3.0 kPa.

III. Temperature Distribution of Lung

Next, we measured the temperature distribution of lung during RFA in order to validate how the internal pressure dependence of the thermal conductivity affects on the ablation region and the duration of treatment

A. Method

Using cool-tip RF system used in clinical cases and the thermo-couples, we measured the temperature around the RF electrode during RFA. RF system consists of an active RF electrode and a control unit to modulate the radio wave and return electrode that collects the current generated by the active electrode (Fig. 6). In general, RFA for lung cancer is performed in case that when the tumor is less than 15 mm in radius. With this in mind, in order to measure the temperature around the RF electrode, three thermo-couples were arranged parallel with the RF electrode at 5 mm intervals, and were able to measure the temperature to a maximum of 15 mm distance from the RF electrode (Fig. 7). On this occasion, the thermo-couples are made from SUS304, which has a high conductivity. Therefore, we reduced the number of the thermocouples as much as possible to prevent the heat generated by the RF electrode being directly transferred to the thermo-couples.
Fig. 8 shows the experimental setup. Temperature distribution was measured at three internal lung pressures, namely 0, 1.0 and 2.0 kPa. At a pressure of 0 kPa the air has not entered into the lung completely, at 1.0 kPa the lung expands to about half the size at 2.0 kPa. And at 2.0 kPa maximum expansion of hog lung takes place, As an experimental procedure, first the hog lung was expanded to a target pressure with the pressure control machine. Second, the RF electrode and the thermo-couples were inserted into the distal portion of the lung, with a certain volume of lung parenchyma after lung expansion. Lastly, the radio wave radionics were turned on. The experimental condition is shown in Table I.

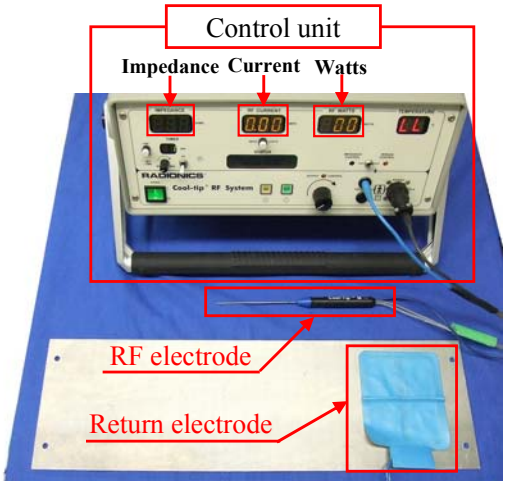

Fig. 6: RF system

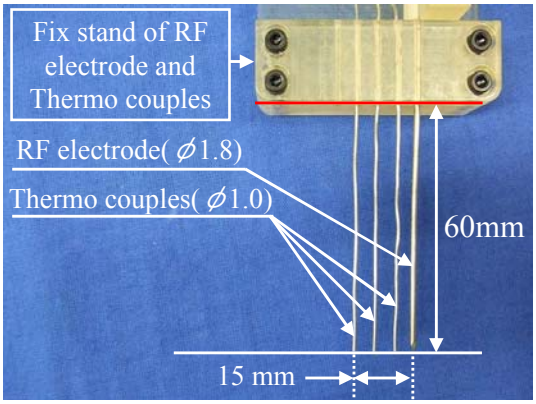

Fig. 7: Position of RF electrode and thermocouples

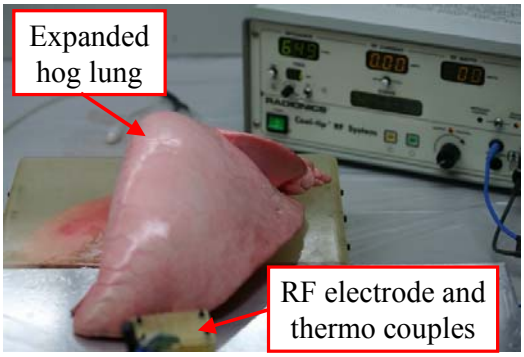

Fig. 8: Experimental setup

TABLE I
Experimental conditions

Pressure kPa	Impedance Ω	Voltage V	Current A	Power W
2.0	630	60	0.09~0.10	6
1.0	300	60	0.20	12
0	268	60	0.21~0.22	12

B. Result

Measured temperature at each thermo-couple is shown in Fig. 9, Fig. 10, and Fig. 11.

1) 0 kPa: Fig. 9 details the result at a lung pressure of 0 kPa, where the ablation time was 500 s. The lung temperature, which was at an initial value of about 20 °C, increased to about 50 °C at a measurement point of 5 mm from the RF electrode tip after an interval of 500 s. The temperature dropped to about 40 °C between the measurement points of 5 mm and 10 mm from the RF electrode tip.

2) 1.0 kPa: Figure 10 shows the result at 1.0 kPa, where the ablation time was 300 s. The temperature, which had an initial value of about 20 °C increased to about 54 °C at a measurement point of 5 mm from the RF electrode tip, and was about 51 and 48 °C at measurement points of 10 and 15 mm, respectively.

3) 2.0 kPa: Figure 11 shows the result at 2.0 kPa. Maximum expansion of hog lung was achieved and the ablation time was 80 s at 2.0 kPa. The lung temperature, which had an initial value of about 16 °C, increased to about 40 °C at a measurement point of 5 mm from the RF electrode tip, and dropped to about 26 and 24 °C at measurement points of 10 and 15 mm, respectively.

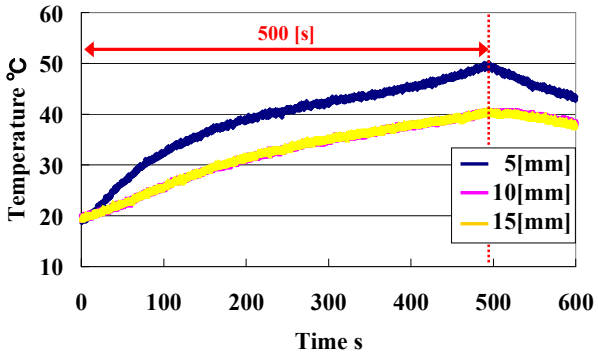

Fig. 9: Temperature distribution at 0 kPa

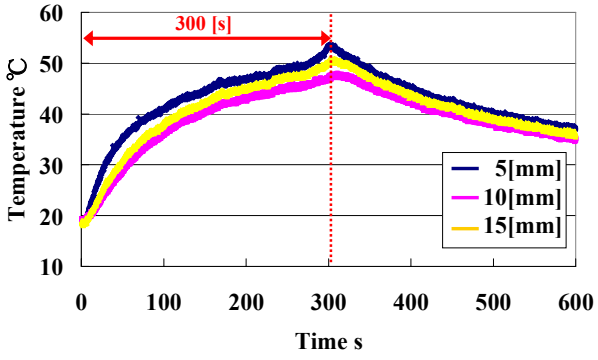

Fig. 10: Temperature distribution at 1.0 kPa

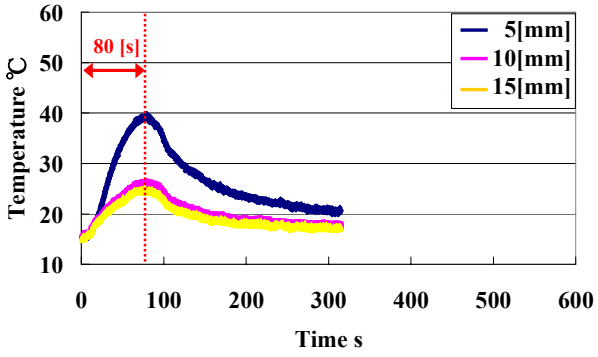

Fig. 11: Temperature distribution at 2.0 kPa

C. Discussion

As a result of the experiment, following two points summarize the experimental result: 1) the cautery time was shorter with increasing lung internal pressures. 2) Maximal temperature at 5 mm from the electrode was the highest at 1.0kPa.

As for 1), it was suggested that the heat generated by the RF needle was focused on only a limited region of tissue at high internal pressure due to the existence of the lung internal air. This tendency that the heat is not dissipated into the surrounding area was likely to cause the shorter cautery time at high internal pressure. Then, as for 2), according to the tendency that the heat is accumulated at immediate vicinity of the RF needle at high pressure, maximal temperature at 5.0 mm would have not been observed at 1.0kPa but at 2.0 kPa. It is considered that the temperature within 5 mm from the needle at 2.0 kPa would be higher than that at 1.0kPa although we could not measure the temperature at less than 5 mm from the needle., It is suggested that the heat in the experiment carried out at 2.0 kPa hardly dissipated from RF electrode, and only a small amount of tissue that was in contact with RF electrode increased in temperature. In addition, the greatest difference in temperature was observed between 5 mm and 10 mm at 2.0 kPa. Due to the existence of the lung internal air, it was possible to focus the heat generated by the RF electrode on a limited region.

The phenomenon that the heat is focused on only at immediate vicinity of the RF needle was likely to be correlated with the changing tendency of the thermal conductivity of lung with internal pressure. As a result of measurement of internal pressure dependence of lung thermal conductivity, lung thermal conductivity was decreased as pressure rises. In general, temperature in the high thermal conductivity area becomes low because heat input into the area quickly flows into surrounding areas and does not accumulate. In contrast, temperature in low thermal conductivity areas becomes higher than that at surrounding areas because heat flows into surrounding areas slowly and can accumulate. In other words, thermal conductivity at a specific point is inversely proportional to the temperature at that point. According to the relation between the thermal conductivity and temperature at specific point, it was confirmed that the lower thermal conductivity at high internal pressure compared to that at low internal pressure resulted in higher temperature in the immediate vicinity of the RF needle.

IV. Conclusions and Future work

In this paper, firstly we have presented data concerning the dependence of thermal conductivity on lung internal pressure using the unsteady hot wire method. Next, using a hog lung, we measured temperature distribution at three internal pressures. From the experiments, it was suggested that lung internal air had an considerable effect on heat transfer. Heat was focused due to increasing lung electric resistivity as a result of increasing the internal lung pressure [11]-[12]. Therefore, it is suggested that lung thermal conductivity and electric resistivity are important factors with regard to RF ablation in the lung.

In the future, more detailed validations of the dependence of thermo and electric physical properties on lung internal pressure will be necessary. At the same time, as we carry out additional studies on lung properties, we will further develop the ablation simulator. The planning and navigation system will also be further developed to enable its use in safe and precise clinical RFA treatment for lung tumors.

References

[1] T. Hiraki, H. Gobara, H. Mimura, Y. Sano, T. Tsuda, T. Iguchi, H. Fujiwara, R. Kishi, Y. Matsui, S. Kanazawa (2010) Dose tumor type affect local control by radiofrequency ablation in the lungs?. European Journal of Radiology 74 : 136-141

[2] R. A. Mctaggart, D. E. Dupuy, (2007) Thermal Ablation of Lung Tumors. Tech Vasc Interventional Rad 10 : 102-113

[3] Y. Miao, Y. Ni, H. Bosmans, J. Yu, J. Vaninbroukx, S. Dymarkowski, H. Zhang, G. Marchal (2001) Radiofrequency Ablation for Eradication of Pulmonary Tumor in Rabbits. Journal of Surgical Reseach 99 : 265-271

[4] A. Pennathur, G. Abbas, R. J. Landreneau, J. D. Luketich (2008) Radiofrequency Ablation for the Treatment of Stage 1 Non- Small Cell Lung Neoplasm. Semin Thorac Cardiovasc Surg 20 : 279-284

[5] S. N. Goldberg (2001) Radiofrequency tumor ablation: principles and techniques. European Journal of Ultrasound 13 : 129-147

[6] T. Schneider, D. Reuss, A. Warth, P. A. Schnabel, A. v. Deimling, F. J. F. Herth, H. Dienemann, H. Hoffmann (2010) The efficacy of bipolar and multipolar radiofrequency ablation of lung neoplasms – results of an ablate and resect study. European Journal of Cardio-thoracic Surgery

[7] H. Watanabe, Y. Kobayashi, M. G. Fujie (2008) Modeling the Temperature Dependence of Thermal Conductivity: Developing a System for Robot-Assisted RFA therapy. in Proceedings of the 2nd IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics : 483-488

[8] H. Futami, T. Arai, H. Yashiro, S. Nakatsuka, S. Kuribayashi, Y. Izumi, N. Tsukada, M. Kawamura (2006) A Heat Conduction Simulator to Estimate Lung Temperature Distribution During Percutaneous Transthoracic Cryoablation for Lung Cancer. JSMBE 44 (3) : 460-466

[9] L. E. Olson (1991) Regional compliance and bronchial pressure-diameter relationship in expanded pig lungs. Respiration Physiology 86 : 25-39

[10] D. D S. Collie, N. J. Watt, P. M. Warren, I. Begara, L. Lujan (1994) Exponential analysis of the pressure-volume characteristics of ovine lungs. Respiration Physiology 95 : 239-247

[11] H. Luepschen, D. v. Rissen, L. Beckmann, K. Hameyer, S. Leonhardt (2008) Mdeling of Fluid Shifts in the Human Thorax for Electrical Impedance Tomography. IEEE TRANSACTIONS ON MAGNETICS 44 (6) : 1450-1453

[12] L. A. M. Mello, C. R. d. Lima, M. B. P. Amato, R. G. Lima, E. C. N. Silva (2008) Three-Dimensional Electrical Impedance Tomography: A Tomology Optimization Approach. IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING 55 (2) : 531-540