

Effect of Radiofrequency Irradiation on Hepatocarcinoma

Hala Moustafa Ahmed, Moustafa Moustafa Ahmed¹, Amira Hamed Mohamed, Mohamed Sameh Nasr²

¹Medical Biophysics,

²Radiology.

Faculty of Applied Medical Science, October Six University, Giza, Egypt

Abstract: *Hepatocellular Carcinoma (HCC) is one of the most common and dangerous diseases that attacks the human liver, it is considered the fifth cause of death worldwide, in Egypt a high incidence of HCC had been reported, there is a strong association between HCV infection & cirrhosis and HCC. The aim of this study is to study the texture, density and the progress of the hepatocellular carcinoma before and after the treatment, using the modern screening modalities such as computed tomography, ultrasound and laboratory investigations such as tumor marker examinations alpha-fetoprotein, alanine transferencees (AFP, ALT) and the temperature induced by the RFA inside the tumor tissue. The basic principle of radiofrequency ablation depends on the effect of temperature induced by the radiofrequency machine which had proved its ability to cause complete ablation of the HCC. So we had used specific mathematical equations to calculate the degree of temperature induced by the radiofrequency wave during the treatment using the available parameter current, watt, impedance of the tumor cells that can be easily monitored during the treatment. This study proved that radiofrequency ablation of hepatocellular carcinoma had a very high effect in destroying the tumor cells and this was monitored by computed tomography, by tumor markers and mathematical calculations. The temperature rise induced by RF during the treatment reaches 100 °C and more and ablation occurs at 4-10 min. At low power temperature at tumor surface varied from 60-225 °C and at high power temperature varied from 140-179 °C. At low power temperature at electrode surface varied from 88-223 °C and at high power temperature varied from 143-278 °C. The total complete necrosis rate after the first session was (87.5%). The total complete necrosis rate after multiple sessions was 95.8%. The total complete necrosis rate after multiple sessions was 95.8%. Mean ALT activity measured before treatment were average of males group (50.16± 12.8 S.D IU/L), and average of females group (58.37±12 S.D IU/L), mean AST measured before treatment were average of males group (46.9±19.1S.D IU/L), and average of females group (52.8±13.8S.D IU/L). Mean HCV-RNA measured before treatment were average of males group (78.3 ± 11.3 S.D copies /ml), and average of females group (84.5 ± 6.35 S.D copies /ml). The normal ranges for HCV-RNA in males and females are (>2 x10⁶ copies /ml). Pretreatment CT with contrast shows enhanced tumors. After RF ablation HCC have been replaced by a larger non enhanced necrotic area.*

Keywords: Hepatocarcinoma-Image guided-Radiofrequency ablation

1. Introduction

Hepatocellular carcinoma (HCC) is one of the most common malignant neoplasms in the world and is the main cause of death in patients with liver cirrhosis. ⁽¹⁾In Egypt, HCC incidence rates were estimated to be between 5 and 7 per 100,000 populations per year. The incidence of hepatocellular carcinoma (HCC) is still rising, making it one of the most common malignancies worldwide. ⁽²⁾ Up to now, surgical resection (SRE) has been considered the first choice treatment. ⁽³⁻⁴⁾

In the recent past RFA was mainly reserved for patients with compromised hepatic function, who were not eligible for surgery. It was also reserved for patients with smaller tumors, since Percutaneous ablative procedures were considered less efficacious for bigger HCC ⁽⁵⁾. The heating effect of alternating radiofrequency (RF) in biological tissue was first described by the French physiologist Jaques D'Arsonval (1851–1940) in the late nineteenth century. In the early 1990s the Percutaneous use of needle like probes for interstitial thermal ablation of tumor tissue was reported for the first time. Since then enormous development of Percutaneous RF technology has taken place. ⁽⁶⁾ Recently the theoretical modeling had applied to the study of RF heating techniques, and focuses on relatively new therapies, such as cardiac ablation ⁽⁷⁾, cancer ablation ⁽⁸⁾ and cornea heating ⁽⁹⁾.

However, other groups have used previous theoretical models to study different aspects of the RF heating phenomenon.

At the last five years the computer modeling of RF ablation offers several unquestionable advantages over the experimental approach. For this reason, it has become an essential tool to complement experimental studies on RF ablation techniques. ⁽¹⁰⁾ These advantages will provide inestimable help to the research and development processes of the manufacturers of RF ablation systems. This is an important advantage, but in addition, and as I have gathered from my experience of cooperation with surgeons, radiologists, and cardiologists, RF ablation models offer valuable assistance in explaining the biophysical phenomena involved in the RF heating of biological tissues. ⁽¹⁰⁾ In other words, the models are excellent didactic tools that enable the users of RF ablation systems to become familiar with the equipment and procedures, and thus indirectly enhance the safety and efficacy of the therapies. ⁽¹⁰⁾ The future of theoretical RF ablation modeling appears to lie in, Accurate modeling of the electrical and thermal characteristics of biological tissues, not only those that are temperature-dependent, but also time-dependent, i.e. to quantify the relations between the values of the characteristics and the thermal damage function. In addition, these relations offer irreversible effects above a certain thermal level ($\approx 70-80^{\circ}\text{C}$), or over a specific value

of a thermal damage function⁽¹¹⁻¹²⁾. Although the best treatment for resectable liver tumor remains surgical resection,⁽¹²⁻¹³⁾ survival rates achieved by tumor ablation (TA) have been sufficiently promising that some centers have started to advocate trials comparing resection with ablation. Limitations that favor tumor recurrence following TA are common to all techniques, but some of those that did not enter clinical trials due to the disadvantage of long ablation times could help in particular clinical settings. Furthermore, newer techniques like microwave (MW) have intra-operative advantages over the older RF in terms of faster execution times clearly demonstrated in dose-response studies.⁽¹²⁻¹³⁻¹⁴⁾

1.1 Aim of the work

The main purpose of this study is to compare the temperature distribution and tissue necrosis patterns for a hepatocellular carcinoma after radiofrequency ablation therapy.

2. Materials and Methods

2.1 Study Patients

A 20 patients were included in this study proved to have HCC and were treated by RFA alone or with combined therapies (RFA /TCAE/PEI), fulfilled the following inclusion criteria: Presence of a single up to 5 cm in diameter or multiple (maximum three) focal lesions of not exceeding 3 cm in diameter each, absence of extra hepatic spread, absence of vascular and biliary invasion, absence of portal vein thrombosis (main trunk or its branches) and absence of marked bleeding diathesis (Prothrombin concentration should be over 60% and platelet count not be less than 50,000), patients with hepatitis class A or B and those with class C must have less than moderate ascites.

2.2 Radiological assessment

Two coincident imaging techniques (two techniques considered: ultrasound, spiral CT) Focal lesion up to 5 cm with arterial hypervascularization. One imaging technique associated to alpha-fetoprotein (AFP) for Focal lesion up to 5 cm with arterial hyper vascularization AFP levels >200 IU/ml. Cardiac and chest examination, ECG, blood pressure and Blood glucose level were done. A Computed Tomography CT (GE high speed model zx/i) abdomen was performed to all patients before and after the radiofrequency

ablation treatment, for detection of the Hepatocellular carcinoma, the basic principle behind CT is that the internal structure of an object can be reconstructed from multiple projections of the object.

2.3 CT Abdomen Technique

Patient position: supine with arms at head level volume of investigation: from dome of the liver to the aortic bifurcation with Normal slice thickness: 7-10 mm; 4-5 mm for suspected small lesions, Inter – slice thickness/pitch = 1.2 – 2.0, Focal of view (FOV) adjusted to the largest abdominal diameter with no gantry tilt, tube current and exposure time product (mAs) should be as low as consistent with required image quality, windows width: 150-600 Hounsfield units (HU) and preventing movement artifacts by a standard breath hold technique using oral contrast media (barium meal) amount 800ml before one hour from the examination, 200 ml immediately before the examination and intravenous contrast media (ultra vest) amount between 80 and 120 ml based on patient size and indication. Dynamic studies included acquisition of unenhanced images followed by acquisition of enhanced images in the hepatic arterial, portal venous, and delayed phases. Computer-assisted bolus-tracking software was used to determine the optimal scan delay for each patient. Acquisition of arterial phase images started 12 seconds after the automatic detection of aortic peak enhancement (120 H). The portal and late venous phases started 55 and 120 seconds after aortic peak enhancement.

2.4 Radiofrequency system

It consists of a cool-tip RF generator, RF electrode (valleylab), grounding pads, perfusion pump, IV bag contain sterile water for infusion, adaptor cable, inflow container and outflow container. The cool-tip RF generator is a microprocessor - based coagulator capable of supplying up to 200 watts of RF power, it also continuously measures and displays RF current (0-4000 mA), impedance (0-1000 ohm) and temperature (0-100 C). For tumors of diameter greater than 3-cm, electrode cluster (with individual electrodes spaced 5 mm apart and 2.0 cm of exposed metallic tip) was used. Single cool tip EF electrode is used for tumors less than 3-cm in diameter.

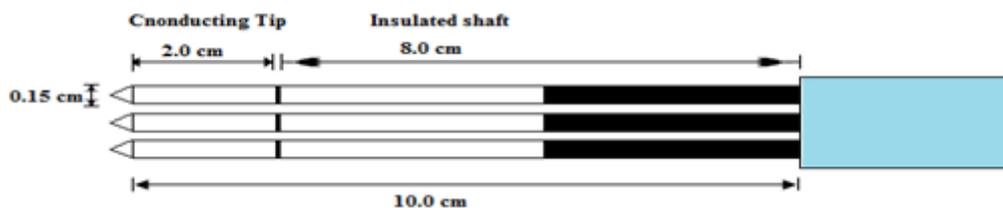


Figure 1: Ablation probe geometry diagram of a cluster needle ablation electrode that is used for hepatic therapeutic treatment

3. Radiofrequency Ablation Technique

Each application of RF energy lasted 12–15 minutes for tumors 2-3cm and 20-25 minutes for tumors up to 5cm; The

RF electrodes were attached to a 500-kHz RF generator (Radionics) capable of producing 200 W of power. During the procedure, tissue impedance, RF watts, RF current was monitored by using circuitry incorporated within the generator. The skin is cleaned with providing iodine

(Betadine) (which also served as a contact medium). Ultrasound guidance using a 3.5 MHz probe by free hand technique for lesions located in the right lobe, an intercostals approach with the patient in the left lateral decubitus position was generally performed, For lesions located in the left lobe, a sub costal approach was most often used. Ultrasound machine used in the present work and insertion of the RF electrode under the guidance of the ultrasound. The size of the tumors was initially measured by conventional US, planning a safety margin at least 5 cm of the surrounding tissue except in cases of HCC with poorly defined borders for which our goal was an ablation margin of 1.0 cm, Tumors larger than 3.5 cm in diameter were ablated with multiple overlapping spheres.

4. Thermal Mechanisms

The bioheat equation below was employed to analyze heat generation from electric energy. We solved the bioheat equation to obtain the thermal distribution in hepatic cancer tissue.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + J \cdot E - h_{b1}(T - T_{b1}) - Q_m \quad (17)$$

For certain tumor size the time needed for the ablation of the tumor at 100°C was calculated. Also the temperature distribution around the electrode starting deeply from the electrode surface up to the tumor boundary was studied. The bioheat equation below was employed to analyze heat generation from electric energy. We solved the bioheat equation to obtain the thermal distribution in hepatic cancer tissue For certain tumor size the time needed for the ablation of the tumor at 100°C was calculated.

Also the temperature distribution around the electrode starting deeply from the electrode surface up to the tumor boundary was studied.

4.1 Laboratory evaluation

For the determination of serum bilirubin, and albumin. All tests have been done in laboratories, also liver enzymes (SGPT and SGOT) were measured according to the method describes by ⁽¹⁵⁾ And HCV-RNA was detected using (RT-PCR).

4.2 Statistical Analysis

The local ethic committee approved this study .Informed consent was obtained from each patient included in this study .Data were expressed as mean \pm standard error (S.E).Data analysis was made by Fisher's exact and Pearson's correlation tests. Using SPSS for Widows (Chicago, II, USA) when appropriate $p < 0.05$ was considered statistically significant.

5. Results

5.1 Baseline Clinical characteristics and clinical courses of Patients

In this study, baseline characteristics of the 20 patients were summarized in (Table 1). The age of the patients ranged from 39 to 74 years and the mean age 56.5 years. As regards their sex, 13 were males (35%) and 7 were females (18.5%), the mean ALT activity measured before treatment were average of males group (50.16 \pm 12.8 S.D IU/L), and average of females group (58.37 \pm 12 S.D IU/L), mean AST measured before treatment were average of males group (46.9 \pm 19.1S.D IU/L), and average of females group (52.8 \pm 13.8S.D IU/L), The normal ranges for ALT and AST in males are (Up to 40 IU/L and Up to 37 IU/L, respectively) normal range for ALT and AST in females is (Up to 39 IU/L and Up to 36 IU/L, respectively). Mean albumin measured before treatment were average of males group (3.04 \pm 0.56 S.D g/L), and average of females group (2.7 \pm 0.35 S.D g/L), mean bilirubin measured before treatment were average of males group (1.4 \pm 0.61 S.D g/L), and average of females group (1.2 \pm 0.36 S.D g/L). The normal ranges for albumin and bilirubin in males were (3 - 5 g/L) and (0.2 - 1 g/L) respectively, normal range for albumin and bilirubin in females were (3 - 4.6 g/L) and (0.2 - 1 g/L), respectively. Mean HCV-RNA measured before treatment were average of males group (78.3 \pm 11.3 S.D copies /ml), and average of females group (84.5 \pm 6.35 S.D copies /ml). The normal ranges for HCV-RNA in males and females are (>2 $\times 10^6$ copies /ml).

Table 1: Baseline characteristics of study 20 patients

Parameter	Male	Female
SGPT Normal Range (mean \pm S.D)	Up to 40 IU/L (50.1 \pm 12.8)	Up to 39IU/L (58.37 \pm 12.0)
SGOT Normal Range (mean \pm S.D)	Up to 37 IU/L (46.9 \pm 19.1)	Up to 36 IU/L (52.8 \pm 13.8)
Serum albumin Normal Range/(mean+S.D)	3-5 g/L (3.04 \pm 0.56)	3-4.6g/L (2.7 \pm 0.35)
Serum bilirubin Normal Range (mean + S.D)	0.2-1 g/L (1.4 \pm 0.6)	0.2-1 g/L (1.2 \pm 0.36)
HCV-RNA > 2 million copies/ml (mean+ S.D)	(78.3 \pm 11.3) copies /ml	(84.5 \pm 6.35) copies /ml

The different statistical parameters including (Mean \pm S.D) with HCV F=female, M=male, S.D=Standard Deviation.

5.2 Effects of Radiofrequency Ablation on HCC

The temperature distribution of the radiofrequency at the electrode and tumor surfaces was calculated using estimated theoretical calculations.

Table 2: Temperature distribution C° at electrode surface after application of low radiofrequency powers (80: 150 watt) with mean= 130 ± Standard error= 2 and after application of high radiofrequency powers (145:186 watt) with mean= 160.1 ± Standard error = 2.6.

RF Power (Watt)		Tumor Radius (M)	Ablation Time (Min)	Temperature at Electrode Surface (C°)	
Minim	Max			At Min Power (watt)	At Max Power(watt)
84	175	0.048	4	88.2599174	143.79149
135	180	0.048	6	158.33847	198.78463
140	184	0.048	5	142.817141	176.07396
123	165	0.0425	8	175.582674	222.90359
130	170	0.0425	9	199.526274	249.53436

Table 3: Shows the Temperature distribution C° at tumor surface after application of low radiofrequency powers (80: 150 watt) with mean= 113.7 ± Standard error= 1.7, and after application of high radiofrequency powers (145:186 watt) with mean= 138.2 ± Standard error = 2.2.

Radiofrequency Power (Watt)		Tumor Radius (M)	Ablation Time (Min)	Temperature at Tumor Surface	
Min	Max			AtMin Power(watt)	at Max Power(watt)
84	175	0.048	4	48.09452862	60.1136013
135	180	0.048	6	63.26210097	72.0161346
140	184	0.048	5	59.90271535	67.1007116
123	165	0.0425	8	80.21124807	94.9663084
130	170	0.0425	9	87.67706497	103.270008

Table 4: Shows the Minimum time required for ablation after application of fixed power (80watt and 186 watt) and different distances from the electrode tip (0.01:0.05 m).

Min time required for ablation(Sec)		The distance from the center of the tumor(m)	Max RF Power (Watt)	Min RF Power (Watt)
186 W	80 W			
5.36267	12.47556515	0.01	186	80
18.11816	42.20883758	0.015	186	80
43.03545	100.5332398	0.02	186	80
84.34076	197.9281811	0.025	186	80
146.4874	346.159968	0.03	186	80
234.2915	559.134935	0.035	186	80
353.113	854.1587617	0.04	186	80
509.0962	1253.851406	0.045	186	80
623.4826	1556.312834	0.048	186	80

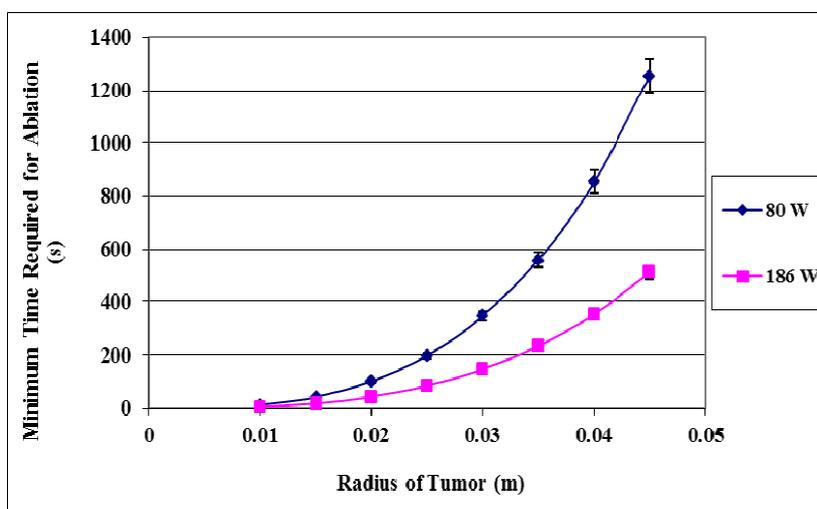


Figure 2: Effect of minimum time required for ablation (sec) on radius of the tumor (m)

6. Discussion

Radiofrequency ablation (RFA) is a local ablation technique designed to destroy the tumor by heating. Alternating current passing from an electrode into the surrounding tissue causes ions to vibrate and generate heat in the tissue. Increased current leads to more vigorous ionic motion and increased temperature over a period of time, eventually leading to coagulation necrosis and cell death.⁽¹⁸⁾

The evidence in the medical literature showed RFA was more effective than other local ablative therapies, and supported its use in the treatment of unrespectable small HCC, recurrent

small HCC, and as bridging therapy before liver transplantation, and as a primary treatment in competition with partial hepatectomy for resectable small HCC.⁽¹⁹⁾ In the present work we studied the effect of radiofrequency waves on hepatocellular carcinoma (HCC), by studying the effect of different radiofrequency powers (low and high powers) on the tumor temperature distribution around the RF insertion electrode.

In this work a mathematical studies have been performed to describe the rate of tumor temperature rising around the RF electrode and its effect on the tumor ablation. Our results showed that the ablation duration used in all cases ranging from 4-10 min. At low RF power, temperature varied from

88-223 °C and 60-225 while at high RF power, the temperature varied from 143-278 °C and from 140-179 °C at the electrode and tumor surface, consequently. Lesions continue to grow while temperature envelopes collapse after ablation since sufficiently high temperature is present to accrue tissue damage. In accordance to our results when the temperature of the electrode increases the tumor tissue was ablated and this was under ultrasound guidance and followed up with CT and alpha fetoprotein and a sudden increase in electrical impedance occurred. The efficacy of RFA can be assessed with contrast-enhanced ultrasound; contrast enhanced dynamic CT (CECT) or contrast-enhanced magnetic resonance imaging (MRI). A successful RFA treated area of HCC is nonenhancing on CECT and tends to be larger than the original tumor.⁽¹⁹⁾ In this study we clarify the important role of contrast enhanced dynamic CT, all patients had pass through a routine CT abdomen with contrast and ultrasound examinations before and after treatment. The study was done under guidance of ultrasound. The texture of the tumor varied from before and after RF treatment this texture is monitored using abdominal CT with contrast before and after the treatment this variation in texture is caused because of that HCC is a malignant tumor which is supplied with blood vessels so when injecting the patient with contrast media before RF treatment the tumor appears a bright (hyper dense), but after Applying the RF treatment the texture appears to be black (hypodense), this means that the radiofrequency waves had applied the appropriate temperature to this tumor and destroyed all of its blood supplies. Also this is proved by laboratory investigation by measuring AFP before and after the treatment. The effectiveness of RFA. For lesions larger than 3 cm could be increased by several applications or adjuvant therapies should be considered to increase the diameter of coagulation hyperthermic cellular sensitization by chemotherapy⁽²⁰⁾, vascular clamping⁽²¹⁾, or cellular ischemia (chemoembolization)⁽²²⁾ and alteration of electric and thermal conductivity (instillation of saline injection)⁽²³⁾. Recent progress in bipolar electrodes could provide better control of the shape of large coagulations⁽²⁴⁾. HCC is the third leading cause of cancer-related death and the fifth - sixth most common cancer⁽²⁵⁻²⁶⁾. The tissue itself is directly heated, rather than the probe itself.⁽²⁷⁾ Above ~50°C, protein denaturation results in irreversible tissue damage.⁽²⁸⁾ Above ~70 °C, coagulation occurs, where collagens are converted to glucose. Above 100 °C, water vapor develops, and tissue charring can occur, this is undesirable, since it raises the impedance and makes the treatment ineffective. Therefore, impedance between the probe and the dispersive electrode is measured during the treatment, and the generator is shut down automatically if the impedance exceeds a certain value (~ 200 to 1000 W, depending on generator type).⁽²⁹⁾

7. Summary and Conclusion

Hepatocellular Carcinoma is one of the most common and dangerous diseases that attacks the human liver, it is considered the fifth cause of death worldwide, in Egypt a high incidence of HCC had been reported, there is a strong association between HCV infection & cirrhosis and HCC. RF ablation (RFA) is a simple, effective, and less expensive technique with a low morbidity compared with surgical treatment RFA can produce significant long-term survival rates and excellent local control. For cirrhotic patients with

early-stage, unrespectable HCC Yet, variable factors determine its efficacy e.g. the size of the lesion, its morphology, the operator expertise and low incidence of major complications is usually associated.

References

- [1] Llovet JM, Burroughs A, Bruix J. Hepatocellular carcinoma. *Lancet* 2003;362:/1907-17.
- [2] Lounsberry W, Goldschmint V, Linke C, et al: The early histologic changes following electrocoagulation. *J. Urol.* 1961; 86:321-9.
- [3] Lee CS, Sheu JC, Wang M, Hsu HC. Long-term outcome after surgery for asymptomatic small hepatocellular carcinoma. *Br J Surg* 1996;/83:/330-3.
- [4] Bruix J, Sherman M. Management of hepatocellular carcinoma. *Hepatology* 2005;/42:/1208-36.
- [5] Llovet JM, Fuster J, Bruix J. Intention-to-treat analysis of surgical treatment for early hepatocellular carcinoma: resection versus transplantation. *Hepatology* 1999;/30:/1434-40.
- [6] Mazzaferro V, Regalia E, Doci R, Andreola S, Pulvirenti A, Bozzetti F, et al. Liver transplantation for the treatment of small hepatocellular carcinomas in patients with cirrhosis. *N Engl J Med* 1996;/334:/693-9.
- [7] Tungjitkusolmun S, Woo EJ, Cao H, Tsai JZ, Vorperian VR, Webster JG. Thermal – electrical finite element modelling for radio frequency cardiac ablation: effects of changes in myocardial properties. *Med Biol Eng Comput.* 2000; 38:562–568.
- [8] Livraghi T, Goldberg SN, Lazzaroni S, Meloni F, Solbiati L, Gazelle GS. Small hepatocellular carcinoma: treatment with radio-frequency thermal ablation versus ethanol injection. *Radiology* 1999;/210:/655-61.
- [9] Lu DS, Yu NC, Raman SS, Limanond P, Lassman C, Murray K, et al. Radiofrequency ablation of hepatocellular carcinoma: treatment success as defined by histologic examination of the explanted liver. *Radiology* 2005;/234:/954-60.
- [10] Wakai T, Shirai Y, Suda T, Yokoyama N, Sakata J, Cruz P, et al. Long-term outcomes of hepatectomy vs percutaneous ablation for treatment of hepatocellular carcinoma 54 cm. *World J Gastroenterol* 2006; 12:546-52.
- [11] LeVeen RF. Laser hyperthermia and radiofrequency ablation of hepatic lesions. *Sem Interven Radiol* 1997; 14:313-324.
- [12] McGahan J, Browning P, Brock J, et al: Hepatic ablation using radiofrequency electrocautery. *Invest. Radiol.* 1990; 25:267-70.
- [13] d'Arsonval A. Action physiologique des courants alternatifs. *Comp. Rend. Soc. Biol.* 1891; 43- 283.
- [14] Clark W, Morgan J, Asnia E: Electrothermic methods in treatment of neoplasms and other lesions with clinical and histological observations. *Radiology.* 2:233-246; 1924.
- [15] Beer E: Removal of neoplasms of urinary bladder; a new method employing high frequency currents through a cauterizing cystoscope. *JAMA.* 1910; 54:1768-9.

- [16] Poon RT, Ng KK, Lam CM: Learning curve for radiofrequency ablation of liver tumors: prospective analysis of initial 100 patients in a tertiary institution. *Ann Surg.* 2004; 239:441-49.
- [17] Tungjtkusolmun S: Finite element analyses for a study of hepatic cancer tissue destruction using monopolar and bipolar radiofrequency ablation. *IJA Biomed Eng* 2009; 2:33-38.
- [18] Mulier S, Mulier P, Ni Y: Complications of radiofrequency coagulation of liver tumours. *Br J Surg.* 2002; 89:1206-22.
- [19] Curley SA, Izzo F, Ellis LM, et al: Radiofrequency ablation of hepatocellular cancer in 110 patients with cirrhosis. *Ann Surg.* 2000; 232:381-91.
- [20] Haemmerich D, Tungjtkusolmun S, Staelin ST, Lee FT, Jr, Mahvi DM, Webster JG. Finite-element analysis of hepatic multiple probe radio-frequency ablation. *IEEE Trans Biomed Eng.* 2006; 49:836-42.
- [21] Berjano EJ, Alio JL, Saiz J. Modeling for radio-frequency conductive keratoplasty: implications for the maximum temperature reached in the cornea. *Physiol Meas.* 2005; 26:157-72.
- [22] Wiley JD, Webster JG. Analysis and control of the current distribution under circular dispersive electrodes. *IEEE Trans Biomed Eng.* 1982;29:381-385.
- [23] Overmyer KM, Pearce JA, DeWitt DP. Measurements of temperature distributions at electro- surgical dispersive electrode sites. *Trans ASME, J Biomechanical Engineering.* 1979; 101:66-72.
- [24] Kim Y, Webster JG, Tompkins WJ. Simulated and experimental studies of temperature elevation around electrosurgical dispersive electrodes. *IEEE Trans Biomed Eng.* 1984; 31:681-92.
- [25] Shiina S, Tateishi R, Arano T, et al. Radiofrequency ablation for hepatocellular carcinoma: 10-year outcome and prognostic factors. *Am J Gastroenterol* 2012;107:569-577.
- [26] Lencioni R, Crocetti L. Local-regional treatment of hepatocellular carcinoma. *Radiology* 2013;262:43-58.
- [27] Elias D, Santoro R, Ouellet JF, et al: Simultaneous percutaneous right portal vein embolization and left liver tumor radiofrequency ablation prior to a major right hepatic resection for bilateral colorectal metastases. *Hepatogastroenterology.* 2004; 51:1788-91.
- [28] Merkle EM, Goldberg SN, Boll DT, et al: Effects of superparamagnetic iron oxide on radio-frequency-induced temperature distribution: in vitro measurements in polyacrylamide phantoms and in vivo results in a rabbit liver model. *Radiology.* 1999; 212:459-66.
- [29] De Baere T, Bessoud B, Dromain C, et al: Percutaneous radiofrequency ablation of hepatic tumors during temporary venous occlusion. *AJR Am J Roentgenol.* 2002; 178:53-9.