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Research Paper

Studying the thermal performance of a bipolar radiofrequency ablation with an improved electrode matrix system: In vitro experiments and modelling

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HIGHLIGHTS

- We made judicious modification to the Penne's equation in the process of developing our model. We consider the liver to consist of tumor and health tissue. The model has been validated with experimental data.
- The proposed electrode system can reduce the tissue volume damage outside the electrodes. The designed building unit with 10 mm inter-electrode distance is the optimal choice to achieve desired ablation zone.
- The influence of blood vessel is relatively small for using this electrode system. A spatial distance of 13 mm is deemed as the safe distance between the wall of the central probe and the large vessel.
- This proposed electrode system demonstrated higher ablation stability even for tissue regions that are close to blood vessels. The system is better suited for matrix-type RFA.

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ABSTRACT

Radiofrequency ablation (RFA) is becoming an effective treatment method for both primary tumors and tumors that have metastasized. Large tumors in difficult anatomic locations can be treated by RFA technologies. However, constant size and regular shape of damage zones cannot be obtained by recent RFA technologies. The aim of this study is to optimize the stability of RFA treatment by employing a newly proposed bipolar electrode system. A hepatic RFA mathematical model is developed by the finite element method approach. The model is validated with the experimental data. This model is then used to verify the reliability and stability of the proposed electrode system. Simulated results showed the cross section of the ablation zone utilizing designed electrode system approximates a square. In addition, the fraction of the necrosed tissue with this electrode pattern turned out to be larger than the fraction with single-probe RFA techniques. This system demonstrated higher ablation stability even for tissue regions that are close to blood vessels. The proposed electrode system is better suited for matrix-type RFA.

1. Introduction

RFA electrodes and ablation system designs have been constantly undergoing calibration and refinement to maximize the diameter of the tumor ablation zone, however the reliability of the RFA therapy has been lagged behind. The major problem of percutaneous single RF probe is the inability to produce a large ablation zone to cover large tumors. This is because that the large RF power induces the undesirable skin burns. To enhance the performance, internally cooled probes in RF ablation has facilitated remarkable progress in obtaining larger ablation zones [1]. Moreover, in many RFA therapy, large tumors have been ablated by sequentially overlapping single electrode [2]. After each ablation, it is very difficult to re-position and calibrate the electrode to correct an untreated site adjacent to the prior zone of ablation. Alternatively, multiple electrodes may be simultaneously applied to deal with large tumors where a single electrode does not succeed in perfectly ablating a large tumor [3–5]. In multiple-electrode RFA treatment, bipolar and multipolar devices are utilized instead of monopolar systems with grounding pads [6,7]. Table 1 describes several representative cases of multi-probe RFA systems.

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Nomenclature

V	electric potential at any point of a volume (V)
T	transition temperatures of tissue (K)
N	normality of physiological NaCl solution
c	tissue's specific heat (J/(kg·K))
k	thermal conductivity (W/(m·K))
Q_{met}	heat sources from metabolism (W/m^3)
Q_{ext}	heat sources from spatial heating (W/m^3)
t	time (s)
C_0	a constant specific heat at temperature below 63.5 °C (J/(kg·K))
$\Omega(t)$	cumulative tissue damage
A	frequency factor (s^{-1})
R	universal gas constant (J/mol·K)
Θ_d	fraction of necrotic tissue

Greek symbols

ρ	tissue density (kg m^{-3})
ω_b	blood perfusion rate (s^{-1})
σ	electric conductivity (S/m)
ω_{b0}	constant blood perfusion of tissue/tumor (s^{-1})

Subscripts

b	blood
T_{ref}	reference temperature

Thus far, clinicians have difficulties in predicting the completeness of tumor ablation zone because of the unreliability of RFA electrode systems. Recent electrodes utilized in RFA treatment are always accompanied by high recurrence rates due to the variability of their size and geometry of ablation zone [8–11]. An undesired ablation volume may also result in damaging too much health tissue or important nearby structure. Rathke and co-researchers completed the comparison of different RFA systems with using ex-vivo livers and verified that standard deviations in RFA treatments are very common [12]. They tested three monopolar and one bipolar/multipolar RFA system to study their abilities to consistently achieve target ablation volumes and found that the coefficients of variation of ablation size using a four RFA systems can be over 10%. A high complex vascular system can result in unstable ablation of tumor. To overcome the limitation of RFA, alternative ablation systems have emerged, such as microwave ablation [13], cryosurgery [14] and laser-induced thermotherapy [15].

Table 1
Several representative multi-probe RFA systems.

RFA system	Definition	Literature
Multiple overlapping mode	The large tumors are treated by sequentially overlapping single-electrode ablations	[2]
Cluster electrodes in conventional monopolar mode	Multiple probes apply simultaneously. A spacer is utilized to ensure parallel insertion and maintain the spacing between electrodes	[3–5]
Multiple electrodes in switching monopolar mode	The multichannel generator is utilized. Power is switched one electrode group to the next	[16–18]
Multi-tined electrodes with saline infusion	A large volume of necrosis was obtained by infusing saline solution through the multi-armed electric probe during production of the RF thermal lesion	[19,20]
Multipolar mode	The electrodes are assigned different voltages, which can create larger coagulation	[6,7]

Mulier and co-researchers suggested a 'building block' (Fig. 1A) for matrix radiofrequency ablation [7]. They proposed that the ablation within the boundaries of the electrodes can be completed with minimal outside ablation when the inter-electrode distance is 2 cm. However, a potential problem with this method is the existence of an obvious depression in the center of anode and cathode, as shown in the temperature contour (Fig. 1B). Therefore, a potential therapeutic inefficiency is borne out. The aim of this study is to propose a new bipolar electrode unit to compose a matrix radiofrequency ablation system and also to verify that it is able to stabilize and complete the targeted ablation zone when the designed electrode system is close to a large vessel.

2. Method

In order to verify the stability and high completion of the designed electrode system, we utilized a finite element method (FEM) analysis by employing the software COMSOL Multiphysics.

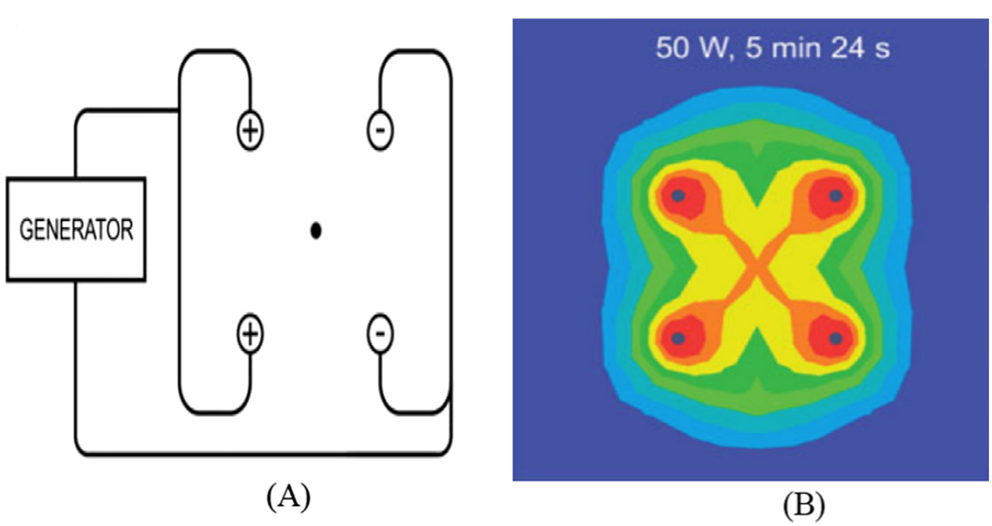

Fig. 1. (A) Mulier and co-researchers' experimental electric wiring scheme: standard 'row' pattern (B) Temperature contour of FEM modelling [7].