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Determination of the Optimal Parameters for Microwave Ablation of Liver Tumor

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Abstract

Microwave ablation is a minimally invasive cancer treatment with high survival and low recurrence rates. Despite the unquestionable benefits of microwave ablation, the interaction between the medical tool and the tissue may cause damage to the surrounding tissue, which can be removed by clarifying the conditions for their development. In addition to clinical methods, computer simulation has proven to be a very effective tool to optimize microwave ablation performance. This study aimed to determine the optimal input power for complete microwave tumor ablation with an adequate safety margin while avoiding injury to surrounding healthy tissue. The liver tumor model was based on a real tumor labeled 1.02 in the 3D-IRCADb-01 database. Calculations were performed for a 10-slot microwave antenna with a frequency of 2.45 GHz using COMSOL Multiphysics. The obtained simulation results revealed that with proper input power, the necrotic tissue was mainly located in the tumor with minimal damage to the surrounding healthy tissue. This study may represent a step forward in planning individual microwave ablation procedures for each patient.**(International Journal of Biomedicine. 2024;14(2):291-294.)**

Keywords: liver tumor • microwave ablation • ablation zone • necrotic tissue

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Introduction

Liver cancer is not only one of the most common cancers in the world, but it is also the fastest-growing cause of cancer-related death.[1-4] Microwave ablation (MWA) at 2.45 GHz is considered as a minimally invasive procedure with a higher overall survival rate than external beam radiation therapy and proton beam therapy.[5,6] Furthermore, MWA is highly recommended as a rapid treatment with a short recovery time for COVID-19 patients with liver tumors.[7] Although the success rate of eliminating small liver tumors by MWA is higher than 85% for large tumors, the completion rates slightly decrease.[8,9]

The mechanism underlying MWA is associated with an increase in temperature above the normal physiological threshold to kill cancer cells with minimal damage to surrounding tissue.[10] A microwave antenna radiates a rapidly oscillating electromagnetic field that causes frictional heating of water molecules in the soft tissues around the field source.[11] The production of reliable near-spherical ablation zones depends on the antenna design. Recently, a compact multi-slot coaxial antenna was built to achieve an optimal ablation shape and proper impedance matching to the target tumor without damaging the surrounding healthy tissues.[12] Besides clinical studies, the role of computational models in predicting microwave ablation outcomes has significantly increased.[13,14]

In this study, simulations were performed using a full three-dimensional (3D) MWA model,[15] which was developed and tested using the COMSOL Multiphysics platform.[16] A realistic tumor model based on a 3D CT scan of the tumor labeled as 1.02 in the 3D-IRCADb-01 liver tumors database (3D-IRCADb)[17] was given special emphasis. The main goal of this study was to determine the optimal input power to ensure complete tumor 1.02 (3D-IRCADb) ablation with minimal damage to the surrounding healthy tissue. Estimating the optimal power will ensure the best ratio of necrotic tissue to healthy tissue.

Methodology

To simulate microwave tissue ablation,[18] the model must contain three fundamental components. The antenna probe model contains a microwave field production in the tissue. In the heat transfer equation, the second component describes the microwave field and blood perfusion as sources of heat and heat sinks, respectively. The third component deals with the effect of the heat on the destruction of the tumor cells. All components of the MWA model are affected by various material parameters that depend on tissue characteristics. Modeling MWA as a multiphysics problem involves modeling multiple physical phenomena, such as electromagnetic wave propagation, heat transfer, and tissue damage, that occur during the procedure.[18] Equations governing the calculations of the electric field distribution through the tissue and the heat generated by the electromagnetic field during MWA[18,19] have been described in previous publications.

In contrast to the frequently used spherical tumor geometry, which is artificial, our simulation model is based on a real tumor labeled as 1.02, which belongs to a female in the database 3D-IRCADb-01, which contains several sets of CT scans of patients (3D-IRCADb).[17] This tumor is relatively large (2.80 cm × 2.34 cm × 2.30 cm) and has an irregular shape, as shown in Figure 1.

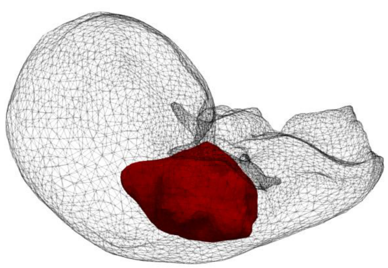

Fig. 1. Schematic view of the liver (triangulated surface) with tumor 1.02 taken from the database (3D-IRCADb) [17] (solid surface).

To determine the optimal input power, numerical simulations were performed for tumor 1.02 from the database (3D-IRCADb)[17] exposed to a frequency of 2.45 GHz and an input power in the range of 25–45 W. The parameters of the biological materials used in the numerical simulations were obtained from the literature.[10,19]

Results

Figure 2 shows the isocontours representing the tumor (triangulated surface) and surrounding healthy tissue (solid light brown surface). The optimal value of the input power corresponded to total tumor ablation with minimal damage to healthy tissues. An input power of 25 W did not ensure complete ablation of the tumor backside. When 35 W was applied, the ablation zone covered the entire tumor, but there was significant damage to healthy tissue. When the whole tumor was destroyed, the isocontours that best fit the necrotic tissue were achieved for an input power of 30 W, while healthy tissue was preserved.

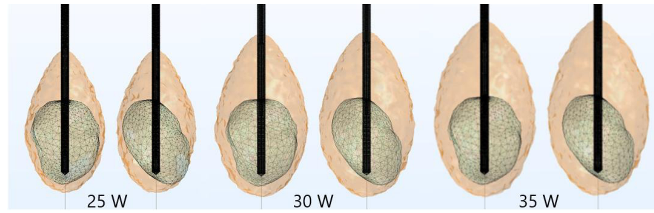

Fig. 2. Isocontours composed of the totally ablated region (solid surface) after 600 s of MWA of tumor 1.02 (3D-IRCADb)[17] (triangulated surface) (for input power of 25, 30, and 35 W).

Figure 3 shows the significance of the proper choice of the input power and ablation time. The ablation time was shortened from 600 to 560, 540, or 520 s when a power of 35, 40, or 45 W was applied, respectively. However, even though the ablation time was shorter, the healthy surrounding tissues were heavily damaged compared with those treated with 30 W for 600 s. These results indicate that the most efficient and safest MWA procedure is not always related to higher input power and shorter ablation time. Due to the dimensions of the tumor and its irregular shape, the formed ablation zones were elongated with a greater length along the shaft of the antenna than the transverse diameter. Elongated shapes are undesirable ablation patterns that cause damage to healthy tissues even if the ablation time is shorter.

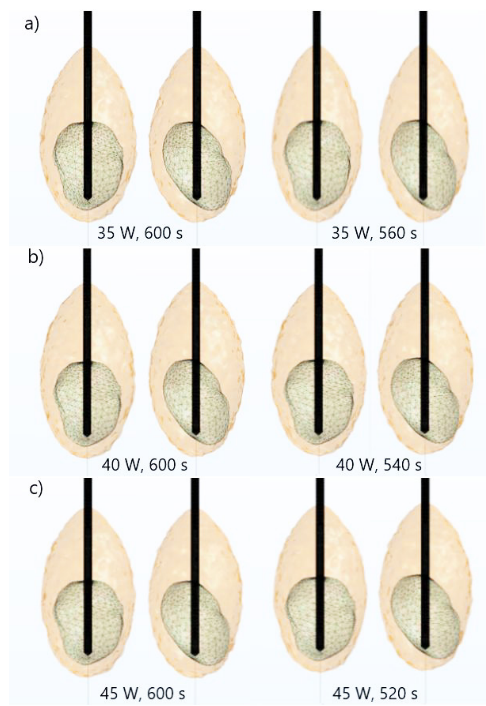

Fig. 3. Totally ablated regions (solid surface) around liver tumor 1.02 (3D-IRCADb)[17] (triangulated surface) for MWA with an input power of a) 35 W, b) 40 W, and c) 45 W during various ablation times.

Figure 4a shows the isocontours calculated for the optimal power of 30 W at temperatures of 40°C, 60°C, 70°C, 80°C, and 90°C.

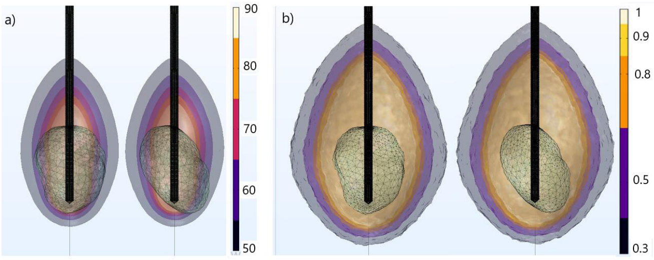

Fig. 4. *Isocontours of a) temperature (50 oC, 60 oC, 70 oC, 80 oC, and 90 oC) and b) fraction of damage (0.3, 0.5, 0.8, 0.9, and 1) corresponding to the front (left) and back (right) sides of the liver tumor 1.02 [17] (triangulated surface).*

The absorbed energy is converted into thermal energy, leading to an increase in tissue temperature. Close to the antenna, where the heat source is strong, the temperature is higher. The temperature increases with the ablation time, reaching a maximum inside the tumor region, where all cancer cells are killed. The temperature decreased as the distance from the antenna decreased, where the heat source weakened. Blood perfusion limits the extent of the heated area. Figure 4b illustrates isocontours related to damage fractions of 0.6, 0.7, 0.8, 0.9, and 1 for an optimal input power of 30 W. The ablation zones were elongated because of the size and irregular shape of the tumor (1.02 3D-IRCADb).[17] The active and passive heating zones can be distinguished. An active heating zone emerges within the tissue closest to the device, with high energy intensity and rapid absorption by tissue. On the other hand, the passive zone appears outside the active zone, far from the antenna.

Discussion

The study aimed to determine the optimal input power for efficient and safe microwave liver tumor ablation. For this purpose, full three-dimensional simulations within COMSOL Multiphysics, a finite element method-based platform, were applied.[16] Calculations were performed for a model of a real liver tumor labeled as 1.02 in the database 3D-ICRADb-01 (3D-IRCADb)[17] exposed to radiation from a 10-slot antenna operating at a frequency of 2.45 GHz. The optimal value of the input power of 30 W was estimated so that the whole tumor could be completely treated with minimal damage to the healthy tissue. The difference between ablation times when the input power was 35, 40, and 45 W, compared with that at 30 W, was approximately 7%, 10%, and 13%, respectively. Ablation time decreased with increasing input power. However, higher input power values may result in undesirable ablation zone shapes, leading to significant damage to healthy tissue. Regardless of the input power, the maximum temperature values were reached inside the tumor regions, where all cancer cells were destroyed. The fraction of damage increased as the ablation time increased. Although a multi-slot coaxial antenna produces a more localized heating pattern for spherical tumors, for realistic tumor shapes, the ablation zones are usually elongated.

Determining the optimal ratio of necrotic tissue to healthy tissue is important for improving the microwave ablation procedure to destroy the maximal part of the tumor while conserving the healthy tissue. It was confirmed that two-dimensional models are not sufficient and that full three-dimensional simulations are necessary for predicting the optimal conditions for microwave ablation, which may be incorporated into medical procedure planning.

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Conflicts of interest

The authors declare no conflict of interest.

References

1. Watson J, Hydon K, Lodge P. Primary and secondary liver tumours. InnovAiT 2016; 9(8):477-82. doi: 10.1177/1755738016653419
2. Sia D, Villanueva A, Friedman SL, Llovet JM. Liver Cancer Cell of Origin, Molecular Class, and Effects on Patient Prognosis. Gastroenterology. 2017 Mar;152(4):745-761. doi: 10.1053/j.gastro.2016.11.048. Epub 2016 Dec 30. PMID: 28043904.
3. Chen JG, Zhu J, Zhang YH, Chen YS, Lu JH, Zhu YR, Chen HZ, Shen AG, Wang GR, Groopman JD, Kensler TW. Liver cancer mortality over six decades in an epidemic area: what we have learned. PeerJ. 2021 Feb 3;9:e10600. doi: 10.7717/peerj.10600. PMID: 33604165; PMCID: PMC7866902.
4. Linn YL, Chee MY, Koh YX, Teo JY, Cheow PC, Chow PKH, Chan CY, Chung AYF, Ooi LLPJ, Goh BKP. Actual 10-year survivors and 10-year recurrence free survivors after primary liver resection for hepatocellular carcinoma in the 21st century: A single institution contemporary experience. J Surg Oncol. 2021 Jan;123(1):214-221. doi: 10.1002/jso.26259. Epub 2020 Oct 23. PMID: 33095920.
5. Villard C, Soler L, Gangi A. Radiofrequency ablation of hepatic tumors: simulation, planning, and contribution of virtual reality and haptics. Comput Methods Biomech Biomed Engin. 2005 Aug;8(4):215-27. doi: 10.1080/10255840500289988. PMID: 16298844.
6. Facciorusso A, Di Maso M, Muscatiello N. Microwave ablation versus radiofrequency ablation for the treatment of hepatocellular carcinoma: A systematic review and meta-analysis. Int J Hyperthermia. 2016 May;32(3):339-44. doi: 10.3109/02656736.2015.1127434. Epub 2016 Jan 21. PMID: 26794414.
7. Afaghi P, Lapolla MA, Ghandi K. Percutaneous microwave ablation applications for liver tumors: recommendations for

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COVID-19 patients. Heliyon. 2021 Mar 6;7(3):e06454. doi: 10.1016/j.heliyon.2021.e06454. PMID: 33748501; PMCID: PMC7966996.
8. Gartshore A, Kidd M, Joshi LT. Applications of Microwave Energy in Medicine. Biosensors (Basel). 2021 Mar 26;11(4):96. doi: 10.3390/bios11040096. PMID: 33810335; PMCID: PMC8065940.
9. Itoh S, Ikeda Y, Kawanaka H, Okuyama T, Kawasaki K, Eguchi D, Korenaga D, Takenaka K. Efficacy of surgical microwave therapy in patients with unresectable hepatocellular carcinoma. Ann Surg Oncol. 2011 Dec;18(13):3650-6. doi: 10.1245/s10434-011-1831-z. Epub 2011 Jun 15. PMID: 21674268.
10. Tehrani MHH, Soltani M, Kashkooli FM, Raahemifar K. Use of microwave ablation for thermal treatment of solid tumors with different shapes and sizes-A computational approach. PLoS One. 2020 Jun 15;15(6):e0233219. doi: 10.1371/journal.pone.0233219. PMID: 32542034; PMCID: PMC7295236.
11. Karampatzakis A, Kühn S, Tsanidis G, Neufeld E, Samaras T, Kuster N. Antenna design and tissue parameters considerations for an improved modelling of microwave ablation in the liver. Phys Med Biol. 2013 May 21;58(10):3191-206. doi: 10.1088/0031-9155/58/10/3191. Epub 2013 Apr 19. PMID: 23603829.
12. Ge M, Jiang H, Huang X, Zhou Y, Zhi D, Zhao G, Chen Y, Wang L, Qiu B. A multi-slot coaxial microwave antenna for liver tumor ablation. Phys Med Biol. 2018 Sep 6;63(17):175011. doi: 10.1088/1361-6560/aad9c5. PMID: 30102247.
13. Racila M, Crolet JM. Numerical simulation of thermoablation in living tissues. Computer Methods in Biomechanics and Biomedical Engineering 2011;14(sup1): 279-80.
14. Chiang J, Wang P, Brace CL. Computational modelling of microwave tumour ablations. Int J Hyperthermia. 2013 Jun;29(4):308-17. doi: 10.3109/02656736.2013.799295. PMID: 23738698; PMCID: PMC3768158.
15. Radjenović B, Sabo M, Šoltes L, Prnova M, Čičak P, Radmilović-Radjenović M. On Efficacy of Microwave Ablation in the Thermal Treatment of an Early-Stage Hepatocellular Carcinoma. Cancers (Basel). 2021 Nov 18;13(22):5784. doi: 10.3390/cancers13225784. PMID: 34830937; PMCID: PMC8616542.
16. Heat Transfer Module 1986-2020. Burlington (MA): COMSOL, Inc. https://www.comsol.com/heat-transfer-module
17. 3D-IRCADb. Available online: https://www.ircad.fr/research/3dircadb/
18. Radmilović-Radjenović M, Bošković N, Sabo M, Radjenović B. An Analysis of Microwave Ablation Parameters for Treatment of Liver Tumors from the 3D-IRCADb-01 Database. Biomedicines. 2022 Jul 1;10(7):1569. doi: 10.3390/biomedicines10071569. PMID: 35884874; PMCID: PMC9312906.
19. Bošković N, Radmilović-Radjenović M, Radjenović B. Finite Element Analysis of Microwave Tumor Ablation Based on Open-Source Software Components. Mathematics. 2023;11:2654.