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Percutaneous Ablations: Minimally Invasive Oncology Treatment

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ABSTRACT

In this paper, three different oncology treatment modalities are evaluated: radiofrequency ablation, microwave ablation, and cryoablation therapy. Image guidance is crucial in allowing for the accurate placement of electrodes to ensure tumor tissue necrosis with the use of ablation therapy. Additionally, the safety and efficacy of each treatment modality is discussed. Radiofrequency ablation uses alternating electrical currents to cause tissue necrosis. While effective, the use of radiofrequency ablation is limited due to an inability to deliver electrical energy in tissues with high impedance. Microwave ablation therapy delivers electromagnetic fields to allow for ablation and is continuing to grow in use as it is effective and efficient in causing tumor necrosis, as demonstrated by the LUMIRA trial. Cryoablation therapy freezes tissues in order to destroy tumor tissue. Although there have been cases of cryoshock, cryoablation is effective in treating cancers like hepatocellular carcinoma and lung tumors.

Introduction

Solid organ cancers in humans are a growing problem, most of which are extremely lethal. Treatment options include surgery and chemotherapy, which can both lead to further complications and side effects. Percutaneous image-guided ablation therapy is a treatment modality with less risk and is minimally invasive. Ablation therapy consists of thermal techniques and image guidance to allow for cellular destruction at the designated site. The three main methods of thermal ablation are radiofrequency ablation, microwave ablation, and cryoablation. Each of these techniques comes with advantages and disadvantages. These benefits and risks must be weighed in order to evaluate an effective method for patients to be treated.

Image Guidance

Electrode positioning must be accurate in order for ablation techniques to effectively cause necrosis of the desired target tumor. Diverse imaging modalities are used for image-guidance for RFA procedures such as Magnetic Resonance Imaging (MRI), Computed Tomography (CT), and Ultrasound (US). A real time CT scan combined with US guidance allows for the most accurate positioning of the RFA needle. Imaging is also required before and after scans to ensure treatment efficacy. For further management of malignancy, positron emission tomography (PET) scans and cross-sectional CT scans allow for indication of metastases away from the targeted tissue. In the case of a lung tumor, for example, a preoperative CT scan of the chest would benefit in determining the size and location of the tumor, as well as the best possible tract of the RFA electrode. After the procedure, imaging aids in determining how effective the treatment was for the patient. At about 2-3 weeks after ablation was conducted, the tissue-repairing process should have begun, where granulation tissue replaces necrotic tissue (Smith & Jennings, 2015). This process of repairing tissue can be assessed with postoperative imaging to evaluate how effective ablation was for the patient.

Radiofrequency Ablation

Mechanism

Radiofrequency Ablation (RFA) delivers alternating electric currents to destroy abnormal tissue growth. By reaching temperatures over 60°C, RFA causes nonreversible cellular modification. Ionic agitation, alternating electric currents to create ion friction, allows for heat production by delivering a sinusoidal current with a frequency of 400-500 kHz. The three different types of heating that are employed include resistive heating, conduction, and convection. Resistive heating works in proportion to the density of RFA energy in human tissue; tissues with higher electrical resistance generate more heat energy when the current passes. Conduction differs according to tissue type and works to heat by establishing a heat gradient to pass energy on from tissue regions with higher temperature to neighboring tissues with lower temperature. Convection, commonly used in liver tumor RFA, effectively causes tissue decay by transporting heat through fluid that surrounds the tissue (de Baère, 2011).

To increase the field of RFA, a single-needle electrode has been adapted to an expandable multi prong probe. In the most used expandable needle, each needle is constructed of about 8-12 electrodes that are introduced to the target tissue once the tissue is punctured. The more electrodes utilized, the more tissue destruction is caused. A bipolar needle is constructed of 2 electrodes placed far apart, to create a high-density field of radiofrequency energy between electrodes (de Baère et al., 2006).

Efficacy

The median reported rate of complete ablation in lung tumors is 90% (Zhu, 2008). Additionally, reports of RFA ablation in tumors less than 2 cm in diameter have been ablated in 78-96% of cases, whereas in tumors larger than 2-3 cm in diameter, RFA has been found less successful (Pennathur, 2010).When examining RFA near critical structures, an animal model study has demonstrated the treatment modality as safe, with RFA resulting in no damage to the myocardium when ablation is conducted near the heart (Steinke, 2003). RFA has been found to be more effective in treating tumors of the lung and liver as opposed to tissues of the kidneys, percutaneous tumors, and bone (Brace, 2009). Due to levels of high impedance in tissues, RFA is often effective in a limited number of tissues. Impedance is the opposition to an alternating current that is often present in organ tissue. When confronted with electrical impedance in the targeted tissue site, RFA is significantly less effective (Lubner, 2010). Like impedance, the heat-sink effect has been exhibited with RFA, which occurs when the ablation site is close in proximity to a blood vessel or lymphatics which cause heat to dissipate and thereby reduce RFA efficacy (Lu, 2002). The main drawbacks of RFA efficacy are associated with inability to penetrate tumors in tissues with high impedance.

Overall, RFA is an effective treatment but is generally not the best treatment option considering the numerous ablation techniques that are also available. Particularly, RFA only allows one probe to be activated at a time. In comparison to other ablation techniques such as microwave or cryoablation in which several probes can be activated at a time, RFA is less efficient. The risk of depositing electrical energy in high impedance tissues, and the frequency of which the heat-sink effect occurs, results in a limited ablation zone. With the ablation zone being limited, the possibility of treating large lesions is reduced. In several cases, RFA was determined to be more painful than techniques such as cryoablation. Therefore, while still functional, the use of RFA is becoming significantly limited due to the several other potential options that are more effective than RFA.

Microwave Ablation

Mechanism

Microwave Ablation (MWA) induces tumor destruction by delivering electromagnetic fields with currencies between 900 and 2450 MHz to malignant tissue. The MWA setup is composed of a microwave generator, flexible coaxial cable, and microwave antenna. The microwave antenna delivers an electromagnetic field to the targeted tissue to generate heat and activate cell necrosis. Two theories are used to explain how tissue necrosis is caused by MWA: the dipole rotation theory and the ionic polarization theory. The Dipole Rotation theory allows for tumor destruction as water molecules are dipole and cause unequal charge distribution. When the electric field is applied, these water molecules rotate, oscillate, and align. Movement of water molecules generates heat, which agitate in the tissue and effectively cause coagulative necrosis or tissue death. Another explanation for which MWA works is the ionic polarization theory. According to the ionic polarization theory, when the electromagnetic field is delivered to malignant tissue, the displacement of ions results in several ionic collisions. The kinetic energy from these ionic collisions is converted into heat energy, which destroys tumor tissue. Once the tissue has reached temperatures above 54°C for at least 3 minutes, total tumor necrosis can be achieved (Gala, 2020).

Efficacy/Safety

MWA has been found to be a highly effective treatment modality, with efficacy rates comparable to that of RFA. Several studies have evaluated the benefits and drawbacks of tumor treatment using MWA. The LUMIRA trial, a controlled and randomized prospective study, evaluated the efficacy of RFA and MWA in ablating lung tumors. In this study, 52 patients with stage IV lung cancer were included. The age range of patients was between 40-87 years and consisted of 15 females and 37 males. The results showed a significant reduction in tumor size after 6-12 months of treatment for both RFA ($p = 0.0014$) and MWA ($p = 0.0003$). However, MWA was evaluated as an overall more effective treatment modality due to its chances of causing less intraprocedural pain (Macchi, 2017). Additionally, in a meta-analysis study, 5 studies of patients receiving MWA were compared to patients receiving RFA. A total of 316 MWA patients were included, along with 332 RFA patients. The results of the study showed an overall higher 1–2 year disease-free survival (DFS) in the MWA group, with a hazard rate ratio (HR) of 1.77. Additionally, the average rates of local tumor progression in a 1-2 year time period was lower than that in the RFA group ($p<0.05$) (Tang, 2023). In a retrospective study, 19 patients who underwent CT-guided MWA of subcardiac tumors, including 6 hepatocellular carcinomas and 16 metastases, were evaluated. The results reflected a primary efficacy rate of 100% and only one grade III complication, being severe shoulder and chest pain (Johnson, 2022). With a perfect complete ablation rate, and only 1 out of 19 of the cases having complications, MWA is an effective method for treating subcardiac tumors.

Cryoablation Therapy

Mechanism

Cryoablation therapy is the process of destroying tissues by freezing. This method of treatment works by applying the Joule-Thomson effect: the theory that gas expansion in a needle tip leads to rapid freezing and thawing. In cryoablation therapy, a needle is injected into a tumor and rapid ice crystal formation, at temperatures between -20°C and -35°C, produces an ice ball which surrounds targeted tissue, through both intracellular and extracellular freezing simultaneously. Intracellular freezing is caused by fast freezing which leads to the direct damage of cellular organelles and the membrane. Extracellular freezing takes place over a longer amount of time. Through extracellular freezing, the extracellular environment becomes more hypertonic, causing water to flow out and dehydrate the cell. Then, the cell is thawed so that the extracellular environment becomes hypotonic, and water flows back into the cell, causing the cell to lyse. The cycle of freezing and thawing is repeated continuously in order to ensure complete tumor ablation (Hinshaw, 2014).

Efficacy/Safety

As a treatment modality, cryoablation has been found highly effective in the treatment of localized tumors. In a study targeting hepatocellular carcinoma (HCC), 685 high risk HCC patients with lesions less than 10mm in proximity to the heart and major vessels, the gastrointestinal tract, or the diaphragm were administered cryoablation as a treatment mechanism. The patients were divided into two groups: high risk and low risk. After 12 months, the high-risk group had a complete ablation rate of 82.1% and the low risk group had a complete ablation rate of 83.9%. Additionally, both groups had an intraoperative success rate of 100%, thereby classifying cryoablation as an effective treatment mechanism for patients with HCC (Zhang, 2024). Another study conducted from June 2014 - June 2018 compared the efficacy of microwave ablation (MWA) to cryoablation in the treatment of malignant lung tumors. Out of 48 patients, 29 were treated with MWA and 19 patients were treated with cryoablation. Patients in the MWA group on average experienced more pain than those of the cryoablation group, tracked by the visual analog scale ($p< 0.001$). Patients who received MWA had a response rate of 72.41% whereas patients treated with cryoablation had a response rate of 73.68%. As there were no significant differences between the two types of treatment, both cryoablation and MWA are effective treatment mechanisms, although cryoablation was found to cause less pain (Li et. al, 2022). The drawbacks of using cryoablation to treat tumors are that it may cause cryoshock due to the freezing temperatures required to cause tumor tissue necrosis. Cryoshock can then lead to several health issues including hypotension or respiratory compromise. In addition, during the freezing and thawing process, the melting ice ball can cause water accumulation, which in some organs such as the lung, could cause pleural effusion which can lead to respiratory compromise. While there is a risk for organ damage by way of freezing when cryoablation is used, there is no risk for excess cautery or coagulation of injured vessels, which is a possibility in microwave or radiofrequency ablation. Therefore, cryoablation is a safe and effective method for treating localized tumors and malignancies due to its ability to cause necrosis in tissue tumors with high complete ablation rates.

Conclusion

Evaluating the efficacy and safety of heat based ablative therapies is crucial in the innovation of cancer eliminating techniques. As medical technologies evolve, and cancer rates continue to rise, treatments which lower the possibilities for debilitating side effects are necessary. Ablative therapies are effective treatment modalities beyond surgery, chemotherapy, and radiation therapy which have high potential to damage tissues surrounding the site of treatment. This way, solid tumors can be treated in a more targeted manner, reducing the chances of infection and further complications. Differentiating between the various types of ablative therapies is valuable as it allows for more targeted therapies in treating solid tumors which are correctly suited to the patient's needs.

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References

Brace C. L. (2009). Radiofrequency and microwave ablation of the liver, lung, kidney, and bone: what are the differences?. *Current problems in diagnostic radiology*, *38*(3), 135–143. https://doi.org/10.1067/j.cpradiol.2007.10.001

de Baère, T., Palussière, J., Aupérin, A., Hakime, A., Abdel-Rehim, M., Kind, M., Dromain, C., Ravaud, A., Tebboune, N., Boige, V., Malka, D., Lafont, C., & Ducreux, M. (2006). Midterm local efficacy and survival after radiofrequency ablation of lung tumors with minimum follow-up of 1 year: prospective evaluation. *Radiology*, *240*(2), 587–596. https://doi.org/10.1148/radiol.2402050807

de Baère T. (2011). Lung tumor radiofrequency ablation: where do we stand?. *Cardiovascular and interventional radiology*, *34*(2), 241–251. https://doi.org/10.1007/s00270-010-9860-8

Gala, K. B., Shetty, N. S., Patel, P., & Kulkarni, S. S. (2020). Microwave ablation: How we do it?. *The Indian journal of radiology & imaging*, *30*(2), 206–213. https://doi.org/10.4103/ijri.IJRI_240_19

Hinshaw, J. L., Lubner, M. G., Ziemlewicz, T. J., Lee, F. T., Jr, & Brace, C. L. (2014). Percutaneous tumor ablation tools: microwave, radiofrequency, or cryoablation--what should you use and why?. *Radiographics : a review publication of the Radiological Society of North America, Inc*, *34*(5), 1344–1362. https://doi.org/10.1148/rg.345140054

Johnson, W., Weekley, A., Suz, P., Parikh, N., El-Haddad, G., Mhaskar, R., & Kis, B. (2022). Safety of CT-Guided Microwave Ablation of Subcardiac Liver Tumors. *Cardiovascular and interventional radiology*, *45*(11), 1693–1700. https://doi.org/10.1007/s00270-022-03235-7

Li, H. W., Long, Y. J., Yan, G. W., Bhetuwal, A., Zhuo, L. H., Yao, H. C., Zhang, J., Zou, X. X., Hu, P. X., Yang, H. F., & Du, Y. (2022). Microwave ablation vs. cryoablation for treatment of primary and metastatic pulmonary malignant tumors. *Molecular and clinical oncology*, *16*(3), 62. https://doi.org/10.3892/mco.2022.2495

Lu, D. S., Raman, S. S., Vodopich, D. J., Wang, M., Sayre, J., & Lassman, C. (2002). Effect of vessel size on creation of hepatic radiofrequency lesions in pigs: assessment of the "heat sink" effect. *AJR. American journal of roentgenology*, *178*(1), 47–51. https://doi.org/10.2214/ajr.178.1.1780047

Lubner, M. G., Brace, C. L., Hinshaw, J. L., & Lee, F. T., Jr (2010). Microwave tumor ablation: mechanism of action, clinical results, and devices. *Journal of vascular and interventional radiology : JVIR*, *21*(8 Suppl), S192–S203. https://doi.org/10.1016/j.jvir.2010.04.007

Macchi, M., Belfiore, M. P., Floridi, C., Serra, N., Belfiore, G., Carmignani, L., Grasso, R. F., Mazza, E., Pusceddu, C., Brunese, L., & Carrafiello, G. (2017). Radiofrequency versus microwave ablation for treatment of the lung tumours: LUMIRA (lung microwave radiofrequency) randomized trial. *Medical oncology (Northwood, London, England)*, *34*(5), 96. https://doi.org/10.1007/s12032-017-0946-x

Pennathur, A., Abbas, G., Schuchert, M. J., Landreneau, R. J., & Luketich, J. D. (2010). Image-guided radiofrequency ablation for the treatment of early-stage non-small cell lung neoplasm in high-risk patients. *Seminars in thoracic and cardiovascular surgery*, *22*(1), 53–58. https://doi.org/10.1053/j.semtcvs.2010.06.002

Smith, S. L., & Jennings, P. E. (2015). Lung radiofrequency and microwave ablation: a review of indications, techniques and post-procedural imaging appearances. *The British journal of radiology*, *88*(1046), 20140598. https://doi.org/10.1259/bjr.20140598

Steinke, K., Arnold, C., Wulf, S., & Morris, D. L. (2003). Safety of radiofrequency ablation of myocardium and lung adjacent to the heart: an animal study. *The Journal of surgical research*, *114*(2), 140–145. https://doi.org/10.1016/s0022-4804(03)00164-1

Tang, Y., Zhong, H., Wang, Y., Wu, J., & Zheng, J. (2023). Efficacy of microwave ablation versus radiofrequency ablation in the treatment of colorectal liver metastases: A systematic review and meta-analysis. *Clinics and research in hepatology and gastroenterology*, *47*(7), 102182. https://doi.org/10.1016/j.clinre.2023.102182

Zhang, W., Wang, Y., Zhao, X., Gao, W., Liu, C., Si, T., Yang, X., Xing, W., & Yu, H. (2024). Efficacy and Safety of CT-guided Percutaneous Cryoablation for Hepatocellular Carcinoma at High-risk Sites. *Academic radiology*, S1076-6332(24)00234-4. Advance online publication. https://doi.org/10.1016/j.acra.2024.04.025

Zhu, J. C., Yan, T. D., & Morris, D. L. (2008). A systematic review of radiofrequency ablation for lung tumors. *Annals of surgical oncology*, *15*(6), 1765–1774. https://doi.org/10.1245/s10434-008-9848-7