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Exploration of Ultrasonic-mediated Precise Ablation Strategies for Tumor Treatment

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Abstract: This article comprehensively explores the application of ultrasonic ablation technology in tumor treatment. It first elaborates on the basic principles of this technology, which utilizes thermal, mechanical, and cavitation effects. The advantages of precise focusing, minimally invasive procedures, and real-time monitoring, as well as limitations such as tissue heterogeneity interference, heat deposition, and acoustic shadow effects, are analyzed. Subsequently, ultrasonic-mediated precise ablation strategies for tumors are introduced, including imaging guidance techniques and ablation technologies such as microwave, cryoablation, and sonodynamic therapy. The therapeutic effects are demonstrated through clinical cases such as ultrasound-guided microwave ablation for the treatment of T1a stage renal cancer. Addressing the issues of inadequate technology popularization and lagging doctor training in promotion and application, solutions such as strengthening medical education and professional training, and further advancing research on equipment performance optimization are proposed, providing references for the development of ultrasonic ablation technology in the field of tumor treatment.

Keywords: Ultrasonic ablation technology; Tumor treatment; Precise ablation strategy; Clinical application; Challenges and strategies

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1. Introduction

As the global cancer incidence rate continues to rise, tumor treatment has become a critical challenge that modern medicine urgently needs to overcome. Traditional surgical, radiotherapy, and chemotherapy methods, although playing a certain role in inhibiting tumor growth, are often accompanied by severe side effects and complications. Surgical removal of tumors inevitably causes damage to surrounding healthy tissues, while radiotherapy and chemotherapy can indiscriminately harm normal cells while killing tumor cells. Therefore, there is an urgent need to explore more precise and minimally invasive tumor treatment options. In this context, ultrasonic ablation technology has emerged as a promising tumor treatment method. Due to its significant advantages such as precision, real-time monitoring, and minimally invasive procedures, it has attracted widespread attention in the medical field. This technology skillfully utilizes the thermal, mechanical, and cavitation effects of ultrasonic waves to rapidly increase the temperature of tumor tissues in a very short time, promoting coagulation necrosis of tumor cells and achieving therapeutic goals. Compared with traditional treatment methods, ultrasonic ablation technology not only minimizes damage to surrounding healthy tissues but also allows real-time monitoring of the ablation area during the entire treatment process, greatly improving the precision and safety of treatment and opening up new paths for tumor treatment.

2. Overview of ultrasonic ablation technology

2.1. Basic principles of ultrasonic ablation

Ultrasonic ablation technology mainly utilizes three biological effects of ultrasonic waves: thermal effect, mechanical effect, and cavitation effect. The thermal effect refers to the conversion of sound energy into thermal energy due to the absorption and scattering of ultrasonic waves by tissues during their propagation, leading to an increase in tissue temperature. When the temperature reaches a certain level, tumor cells undergo coagulation necrosis and are thus destroyed. The principle of ultrasonic ablation is similar to that of a magnifying glass focusing sunlight. By utilizing the tissue-focusable and penetrable properties of ultrasonic waves, the sound waves sent from outside the body are focused inside, instantly raising the temperature at the focal point to above 60%, ablating the diseased tissue without damaging the surrounding tissues [1]. The mechanical effect refers to the mechanical vibration generated by ultrasonic waves during their propagation in tissues, which can directly damage the structure and function of tumor cells. The cavitation effect occurs when ultrasonic waves propagate in liquids, creating tiny bubbles that rapidly expand and collapse under the action of the ultrasonic waves, generating powerful shock waves and local high temperatures that destroy tumor cells [2].

2.2. Advantages of ultrasonic ablation

Ultrasonic ablation technology holds promising prospects in the field of tumor treatment. Its precise focusing technology allows energy to be accurately concentrated on tumor tissues, minimizing damage to surrounding healthy tissues, thereby ensuring treatment effectiveness while reducing additional harm to the patient’s body. During treatment, with the aid of ultrasonic imaging technology, doctors can observe the ablation area in real-time and intuitively, enabling flexible adjustment of the treatment plan to ensure precise and safe treatment. Furthermore, this technology is minimally invasive, eliminating the need for surgery, significantly reducing patient pain and avoiding the risks and complications associated with traditional surgical procedures. It provides patients with a comfortable and safe treatment experience and is expected to become an important tool in tumor treatment [3].

2.3. Limitations of ultrasonic ablation

Despite its significant advantages in tumor treatment, ultrasonic ablation technology has its limitations. Tissue heterogeneity can significantly interfere with the treatment, as bones, air, and other tissues strongly absorb and scatter ultrasonic waves, impeding their propagation and weakening penetration. This can prevent energy from being accurately and efficiently deposited in tumor tissues, significantly reducing the ablation effect. Additionally, heat deposition during treatment can be a challenging issue. If heat cannot be dissipated on time, it can cause thermal damage to surrounding healthy tissues, affecting the patient’s treatment experience and recovery. Furthermore, due to differences in tissue acoustic impedance, ultrasonic wave propagation can produce acoustic shadow effects, reducing the clarity of ultrasonic imaging. This can make it difficult for doctors to accurately observe tumors and ablation areas, seriously affecting treatment precision and posing challenges to the stability and reliability of treatment outcomes.

3. Precise ultrasonic-mediated tumor ablation strategies

3.1. Imaging guidance technology

Imaging guidance technology plays a crucial role in precise ultrasonic-mediated tumor ablation. Imaging techniques such as ultrasound imaging, MRI, and CT provide real-time information on the location, size, and morphology of tumors, assisting doctors in precisely locating the ablation area. Ultrasound imaging, with its real-time capabilities, non-radiation properties, and lower cost, has become the most commonly used guidance technology. While MRI and CT have advantages in image resolution, their higher costs and inability to provide real-time monitoring often limit their use as auxiliary guidance techniques [4]. During ultrasonic ablation, ultrasound imaging can display real-time sonograms of tumor tissue, helping doctors determine the puncture path and ablation range. Through ultrasound imaging, doctors can observe the propagation of ultrasonic waves in tissues and monitor changes in tissue temperature during the ablation process. This allows for real-time adjustment of ablation parameters, ensuring the precision and safety of the treatment. MRI and CT are primarily used for preoperative planning and postoperative evaluation in ultrasonic ablation. With MRI and CT imaging, doctors can gain a detailed understanding of the three-dimensional structure of the tumor and its relationship with surrounding tissues, enabling personalized treatment plans. Postoperatively, MRI and CT imaging can assess ablation effectiveness and facilitate timely detection and management of complications.

3.2. Microwave ablation technology

Microwave ablation technology is a treatment method that utilizes microwave energy to heat tumor tissue, causing coagulation necrosis. With its fast-heating speed and large ablation range, microwave ablation has found widespread application in tumor treatment. During the microwave ablation process, doctors use imaging guidance technology to insert a microwave antenna into the tumor tissue, employing microwave energy to heat the tumor tissue to a lethal temperature, thus eliminating tumor cells [5]. The advantage of microwave ablation lies in its rapid heating speed, which can quickly raise the temperature of tumor tissue to achieve ablation. Additionally, microwave ablation offers a larger ablation range, making it suitable for treating larger tumors. The effectiveness of microwave ablation can be further enhanced by using multiple antennas simultaneously. For instance, in the treatment of liver cancer, doctors can cover the entire tumor with the ablation range by using multiple antennas, thereby improving treatment outcomes.

3.3. Cryoablation technology

Cryoablation technology destroys tumor tissue through low temperatures, causing coagulation necrosis. This method has shown promising results in the treatment of tumors such as prostate cancer and liver cancer. Cryoablation typically uses liquid nitrogen or argon as a refrigerant. With the help of imaging guidance technology, a cryoprobe is inserted into the tumor tissue, rapidly lowering its temperature to several tens of degrees below zero, leading to tumor cell death. The advantages of cryoablation include minimal trauma and fast recovery, making it suitable for patients who cannot tolerate surgery. Furthermore, the ice ball formed during cryoablation can be observed in real-time using imaging technology, aiding doctors in precisely controlling the ablation range. The effectiveness of cryoablation can be further enhanced through multiple freeze-thaw cycles [6]. For example, in the treatment of prostate cancer, doctors can achieve better treatment outcomes by employing multiple freeze-thaw cycles to fully rupture and necrose tumor cells.

3.4. Sonodynamic therapy

Sonodynamic therapy is an emerging tumor treatment method that utilizes ultrasonic waves to activate a sonosensitizer, generating free radicals and local high temperatures to kill tumor cells [7]. This method exhibits high selectivity and non-invasiveness, showing significant application potential. The basic principle of sonodynamic therapy involves injecting a sonosensitizer into tumor tissue and activating it with ultrasonic waves. This activation produces free radicals and local high temperatures, disrupting the structure and function of tumor cells. The advantages of sonodynamic therapy lie in its high selectivity and non-invasiveness. The sonosensitizer is only activated under ultrasonic waves, minimizing damage to surrounding healthy tissues. Additionally, by adjusting the parameters of the ultrasonic waves, doctors can precisely control the ablation range, enhancing the precision of treatment. Sonodynamic therapy can also be combined with other treatment methods to further improve treatment outcomes. For instance, in the treatment of breast cancer, doctors can combine sonodynamic therapy with chemotherapy, using sonosensitizer to enhance the effectiveness of chemotherapy drugs [8].

4. Clinical application case analysis

4.1. Ultrasound-guided microwave ablation for the treatment of T1a stage renal cancer

Ultrasound-guided microwave ablation is a safe and effective minimally invasive treatment method for T1a-stage renal cancer. Using ultrasound imaging technology, doctors can precisely locate renal cancer tumors, then insert a microwave antenna into the tumor tissue, and utilize microwave energy to heat the tumor tissue to a lethal temperature, thereby eliminating tumor cells. Cheng et al. [9] conducted a preliminary clinical study at the General Hospital of the Chinese People's Liberation Army, treating 48 tumors in 44 patients with T1a-stage renal cancer using microwave ablation. The average maximum tumor diameter was (2.79 ± 0.75) cm. The average follow-up period was (18.1 ± 9.3) months, and the results showed that 88.6% of patients completed treatment with one ablation session, while 11.4% required two ablation sessions. 97.7% of patients showed no local recurrence or distant metastasis after ablation therapy. This indicates that ultrasound-guided microwave ablation has high efficacy and safety in the treatment of T1a-stage renal cancer.

4.2. Application of imaging precision-guided minimally invasive ablation therapy in breast cancer

The application of imaging precision-guided minimally invasive ablation therapy in breast cancer has also demonstrated promising results. Through imaging guidance technology, doctors can accurately locate breast cancer tumors and then eliminate them using ablation techniques. New technologies such as hyperthermia therapy, cryotherapy, and microscale electroporation have shown high value in the treatment of breast cancer. Although MRI does not have great specificity as a diagnostic tool, it has strong sensitivity in detecting abnormal tissues and their margins. MRI can detect temperature values slightly below the coagulation threshold, and in modern research, this safety feature is used to confirm the accurate positioning of the target area before focused ultrasound ablation.

In the treatment of liver cancer, cryotherapy is a relatively mature ablation technique compared to radiofrequency ablation and was first applied in the late 1980s. However, the application of image-guided cryotherapy in breast cancer treatment is not as mature as in liver cancer, and there are relatively few reports on cryoablation in breast cancer treatment, indicating the need for further research and development. Imaging-guided irreversible electroporation is also expected to evolve further, with microscale electroporation representing its developmental prospect. This can provide spatial and temporal control for various electrical parameters. Microscale electroporation devices will reduce limitations such as local PH changes, electric field interference, sample contamination, and difficulties in transfection and maintaining the viability of ideal cell types. Integrating microscale engineering with biology has potential benefits for practical applications in life sciences and biotechnology. To facilitate the wider clinical application of imaging-guided microscale electroporation, improvements in efficiency and operational simplicity are required.

4.3. Cases of sonodynamic therapy for tumor treatment

The clinical application of sonodynamic therapy in tumor treatment has also shown promising results. Qi et al. [10] studied the mechanism of sonodynamic therapy and its types of sonosensitizers, finding that sonodynamic therapy exerts antitumor effects through various mechanisms such as ultrasonic cavitation, disruption of the cytoskeleton, mediation of apoptosis, induction of oxidative damage, increased drug transport, reduction of drug resistance, and immune modulation. Sonosensitizers have evolved from early porphyrins and their derivatives to current xanthene derivatives and other types of sonosensitizers, including microparticle-type sonosensitizers, chemotherapy drugs, cytoskeleton-acting sonosensitizers, acridine orange, curcumin, antibiotics, and more. Many domestic and international in vitro and in vivo experiments have confirmed that sonodynamic therapy has a significant killing effect on various tumor cell lines, indicating its broad application prospects in antitumor treatment.

5. Challenges and strategies

5.1. Challenges

Despite the significant advantages of ultrasonic ablation technology in the field of tumor treatment, there are still a series of pressing issues that need to be addressed in its promotion and practical application. The limited popularity of the technology restricts its coverage in the medical field, while the lag in doctors' professional skills training has become a key bottleneck hindering the widespread application of this technology. Ultrasonic ablation technology involves complex operational procedures and specialized medical knowledge, which makes some doctors have a shallow understanding of it and insufficient proficiency in practical operations. This prevents them from fully tapping into and leveraging the technology's vast potential, seriously affecting its application effectiveness and promotion progress in clinical treatment.

5.2. Resolution Strategies

It is urgent to build a solid and efficient system and mechanism for strengthening medical education and professional training. On the one hand, special training courses on ultrasonic ablation technology should be periodically conducted, with course planning progressing from the basics to the advanced. The courses should systematically explain the technical principles, deeply analyze operational essentials, and finally focus on clinical applications. Senior and authoritative experts in the industry should be invited to teach, leveraging their rich experience to present complex theoretical knowledge in an easy-to-understand manner. Through practical demonstrations, doctors can learn standard operational procedures intuitively, followed by adequate practical sessions. Under the guidance of experts, doctors can repeatedly practice to deepen their understanding of the technology and gradually improve their operational skills, laying a solid foundation for clinical practice.

In terms of in-depth research and advancement, efforts should be made to explore effective paths for optimizing the performance of ablation equipment. For sonodynamic therapy, increased research and development investment should be dedicated to the development of new sonosensitizers, aiming to enhance the interaction between ultrasonic waves and tumor cells and significantly improve treatment efficacy. For microwave ablation technology, innovations should start with the design of microwave antennas, improving materials and structures to expand the scope of microwave action and achieve more comprehensive tumor ablation. In the field of cryotherapy, research should focus on the development of new cryoprobes, utilizing advanced technologies to precisely control the freezing range and temperature, improving ablation accuracy, and enhancing the safety and effectiveness of treatment in all aspects. These efforts will lay a solid foundation for the widespread promotion of ultrasonic ablation technology.

6. Conclusion

As a precise and minimally invasive tumor treatment method, ultrasonic ablation technology has shown promising results and application prospects in clinical practice. With continuous technological advancements and innovations, ultrasonic ablation technology will play an increasingly important role in future tumor treatment. Through the application of multimodal image fusion, intelligent, and personalized treatment systems, ultrasonic ablation technology will further improve the precision and safety of treatment, bringing new hope to patients with tumors.

Disclosure statement

The author declares no conflict of interest.

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