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Prevention, Detection, and Management of Complications Associated with CT-Guided Ablation of Pulmonary Nodules

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Abstract

CT-guided ablation delivers precise positioning, minimal trauma, rapid postoperative recovery and repeatable treatment, so it has become a key clinical strategy for pulmonary nodules. As an invasive intervention, this procedure cannot fully eliminate postoperative complications. This review collects domestic and international research papers published in recent years, summarizes four major complications—pneumothorax, pleural effusion, bleeding and pain, and elaborates each complication's incidence, clinical manifestations, risk factors, management protocols and preventive strategies. The summaries in this paper offer clinical references to reduce the incidence of post-ablation complications and advance CT-guided pulmonary nodule ablation toward standardized, precise and safer clinical workflows.

Keywords

CT-guided Ablation, Pulmonary Nodule, Postoperative Complications.

1. INTRODUCTION

A pulmonary nodule refers to a round or oval lesion within the lung with a diameter of ≤3 cm. On imaging, it appears as a solid or subsolid pulmonary opacity with increased density, with well-defined or ground-glass-like margins. It may be solitary or multiple and is not associated with atelectasis, hilar lymphadenopathy, or pleural effusion [1]. Solid nodules with a diameter >8 mm are defined as high-risk nodules. Solid nodules with a diameter ≥15 mm, or those with a diameter between 8 and 15 mm that exhibit malignant features such as Lobar sign, spiculated sign, pleural traction sign, and small-bubble sign, eccentric thick-walled cavities, or the "air-containing bronchioles sign," are also defined as high-risk nodules.

Today, with the widespread use of low-dose computed tomography (LDCT) in lung cancer screening, the detection rate of pulmonary nodules has been rising year by year. Although traditional surgical resection is a curative approach, it has limitations—such as poor surgical tolerance and slow postoperative recovery—for elderly patients, those with underlying comorbidities, or those who refuse surgery. Against such background, CT-guided ablation (including radiofrequency ablation, microwave ablation, cryoablation) has become an important alternative methods in clinic for the treatment of pulmonary nodules. The CT-guided ablation has many advantages, such as precise targeting, minimal trauma, rapid recovery and high reproducibility. Because it is an invasive interventional therapy. This methods can achieve a curative effect, due to it use some energy to generate high temperatures at the lesion site, leading to coagulative necrosis of tumor cells. The CT-guided ablation has clear and important clinical value, but it as an invasive treatment, postoperative complications cannot be completely avoided. This article discusses pneumothorax, pleural effusion, hemoptysis, and pain. Above

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four major complications, and their incidence, clinical manifestations, risk factors, treatment strategies, preventive measures.

2. PNEUMOTHORAX

No matter what ablation method used, pneumothorax is the most common complication. Pneumothorax means that air enters the pleural cavity and subsequently compresses the lung tissue. According to the complication grading criteria of the Society of Interventional Radiology [2], pneumothorax can be classified as mild (asymptomatic or minimal, requiring no specific treatment) or severe (requiring closed thoracic drainage or prolonged hospitalization). Data from multiple domestic and international studies indicate that the incidence rate varies significantly across different studies. Wang's study reported a pneumothorax incidence rate of 10%–65%, with approximately 5%–25% of cases requiring chest tube placement [3]. Xin Shaowei [4] and colleagues analyzed the safety of microwave ablation for lung cancer and found that pneumothorax was the most common complication among 38 lung cancer patients, occurring in 12 cases (an incidence rate of 31.6%); of these, 11 were localized and required only clinical observation. Sun Rui [5] conducted a postoperative analysis of 110 cases of microwave ablation for lung nodules, reporting a pneumothorax incidence of 36.4% (40/110), with 7 cases involving significant pneumothorax requiring closed thoracic drainage. Yoshimatsu [6] et al. reported that delayed pneumothorax can occur after radiofrequency ablation, with an incidence rate of 10.3%. The mechanism of pneumothorax is primarily related to air entering the pleural cavity along the needle tract as the puncture or ablation needle penetrates the pleura into the lung tissue. In addition, patient-related factors such as coughing during the procedure, excessive respiratory movement, and poor elastic recoil of lung tissue may also exacerbate pneumothorax. Localized high temperatures during ablation lead to coagulative necrosis of lung tissue. It also may result in incomplete closure of the needle tract and increase the risk of persistent air leakage. The delayed pneumothrax may be related to the tissue sloughing after ablation, the needle tract delayed opening, or repture of pulmonary bullae.

Although patients with pneumothorax may be asymptomatic, the condition can worsen over time and impair lung elasticity and recoil, leading to decreased ventilation and even respiratory failure, which adversely affects patient prognosis and quality of life. Many researchers are actively identifying risk factors, and numerous studies [7–9] have investigated predictors of post-ablation pneumothorax, including emphysema, age, gender, the number of ablated tumors, tumor location, tumor diameter, and the course of the lung lobe. Wu [10] and colleagues conducted a study on the treatment of pulmonary nodules using percutaneous needle biopsy combined with microwave ablation. They performed univariate and multivariate logistic regression analyses on pneumothorax, a common complication, and found that the occurrence of pneumothorax was associated with the following five risk factors, ranked in order of importance: number of needle insertions > BMI > lesion depth > lesion location > needle diameter.

Management of pneumothorax depends on its severity [11]: a small pneumothorax involves lung collapse of less than 30%, a moderate pneumothorax involves lung collapse of 30–50%, and a massive pneumothorax involves lung collapse of more than 50%. Minor pneumothorax may not require clinical intervention; chest X-rays and monitoring of clinical symptoms are sufficient. Moderate and massive pneumothorax, particularly when accompanied by significant symptoms such as chest tightness and dyspnea, require immediate closed thoracic drainage. Additionally, approximately 10% of patients experience delayed pneumothorax within 3 days post-procedure despite no intraoperative complications; therefore, chest X-rays should be performed within 3 days after ablation to detect delayed pneumothorax as early as possible. To preventing pneumothorax lies in optimizing puncture techniques and perioperative

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management. Firstly, we must insist on the principles of precise localization and single-puncture during the procedure. And also can use some sedatives to reduce patient movement. During the perioperative period, we can use CT to determine the best puncture path, avoid lung fissures, bullae and major blood vessels, and thus reduce puncture attemps. Secondly, the patient education is important. Before ablation, we should tell patients not to cough or take deep breaths during the operation. After ablation, we should advice patients need to rest in a supine position for 4–6 hours, avoid strenuous activity and forceful coughing, and monitor their respiratory status, with routine follow-up chest X-rays or CT scans.

3. PLEURAL EFFUSION

Pleural effusion is the second most common complication following ablation therapy. It refers to the abnormal accumulation of fluid in the pleural cavity. This incidence rate is approximately 20–35%. Li Shuai and other researchers hold that 38 lung cancer patients received microwave ablation treatment, and 23.7 percent of them developed pleural effusion [12]. Wang's team [13] analyzed pneumothorax and pleural effusion after microwave ablation. 23.4 percent of patients got pneumothorax, 33.4 percent suffered pleural effusion, and 44.2 percent had either of the two complications. Sun Rui [5] carried out a study on microwave ablation for pulmonary nodules. The rate of pleural effusion reached 14.5% (16 out of 110 patients), only one patient received thoracic catheter drainage. Most effusions are small in volume and bring no symptoms or clinical impacts. Only a few required puncture and drainage. The mechanism underlying pleural effusion is complex. First, ablation can trigger inflammatory reactions in local lung tissue. More inflammatory mediators leak out. They raise capillary permeability and fluid seeps into the pleural cavity. Second, the ablation needle or puncture needle may damage the pleura. It breaks capillaries. Blood components flow into the pleural cavity. The symptoms of pleural effusion are very similar to those of pneumothorax. They make patients feel chest tightness, shortness of breath and breathing difficulty. We can use imaging tools like chest X-rays to tell these two conditions apart. If infection happens, patients may develop fever and higher inflammatory markers, or even empyema.

To date, there have been limited studies on independent risk factors for pleural effusion. Some studies [14, 15] point out several risk factors that may trigger pleural effusion. These factors include large lesions, multiple nodules treated in one ablation session, lesions too close to the pleura (<10 mm), and long ablation time. Sun Rui [5] suggests that the radiological feature known as the "spiculated sign" is also a contributing factor to the development of pleural effusion. Currently, no detailed research can prove the link between the spiculated sign and pleural effusion so far. However, researchers guess how spiculated sign causes pleural effusion: tumor cells invade surrounding lymphatic vessels, block lymphatic drainage, and finally produce pleural effusion.

In our clinical practice, we have observed that pneumothorax and pleural effusion often occur simultaneously. Follow-up chest X-rays after ablation procedures may reveal the presence of a pneumothorax with pleural effusion; therefore, the treatment and prevention of these two conditions share similarities. Small amounts of pleural effusion do not require special treatment and may resolve spontaneously. However, in cases of moderate to large effusions or when significant dyspnea is present, timely thoracentesis should be performed to drain the fluid, and a drainage bottle should be connected if necessary. In patients who are elderly, immunocompromised, or have diabetes, there is a high risk of empyema; in such cases, antibiotics should be administered concurrently with drainage. In severe cases, intrathoracic fibrinolysis and surgical debridement may also be indicated. To prevent pleural effusion, first assess the patient's underlying conditions preoperatively. Screen for hypoproteinemia, diabetes, and other relevant factors. For patients with hypoproteinemia, administer appropriate albumin supplementation preoperatively to increase plasma colloid osmotic pressure and reduce the likelihood of pleural effusion. For diabetic patients, evaluate the risk of infection preoperatively and administer short-term antimicrobial therapy if necessary. Second, during the ablation procedure, the ablation time should be minimized to avoid excessive ablation that could damage the surrounding pleura and normal tissues. The puncture route should be precisely planned to avoid large areas of the pleura as much as possible. Additionally, a follow-up chest X-ray should be performed promptly after surgery to monitor the patient's symptoms.

4. BLEEDING

Bleeding is a complication that requires close monitoring following ablation procedures, including parenchymal hemorrhage (pulmonary hematoma), hemoptysis (blood in sputum or massive hemoptysis), and hemothorax (accumulation of blood in the pleural cavity). Small bleeding shows cloud-like high-density shadows in the ablation area on CT scans. Heavy bleeding brings clinical signs such as hemoptysis, hemothorax, acute respiratory failure or hemorrhagic shock. Hemoptysis and hemothorax appear most often. The incidence of bleeding ranges from approximately 3% to 40% [16, 17]. Zhuang Liang carried out a study on 38 patients after microwave ablation [18]. Only two patients (5.3%) suffered bleeding. Liu Xiaowei conducted research on 49 lung cancer patients who received microwave ablation [19], which found similar results. Just two patients had hemoptysis, with an incidence rate of only 4.1%. Another study [5] analyzed 110 patients with pulmonary nodules after microwave ablation. It reported a 27.3% incidence rate of pulmonary hemorrhage (30/110). The incidence of pulmonary hemorrhage varies significantly across different studies, likely due to factors such as sample selection and ablation techniques. Radiofrequency ablation uses high-frequency current to heat and coagulate tissue, while microwave ablation increases the kinetic energy of polar water molecules and converts this energy into heat, raising tissue temperature to cytotoxic levels [20]. Both thermal ablation techniques possess blood coagulation effects, so the probability of massive hemoptysis is very low. Cryoablation can optimize the distribution and coverage of ice spheres over the lesion by adjusting the number of cryoprobes, their arrangement, and the number of freeze-thaw cycles. Although cryoablation reduces damage to adjacent healthy tissue, there is a potential risk of increased bleeding, which may result from the melting of ice spheres within the lung parenchyma [21]. A recent study [22] suggests that the incidence of bleeding during liquid nitrogen cryoablation for lung, bone, and soft tissue tumors is manageable.

Sun et al. [5] found that synchronous biopsy during ablation was the only independent risk factor for pulmonary hemorrhage. They speculated that this was because, when using a biopsy needle to obtain tissue samples, the needle cuts into the lesion, damaging small blood vessels within or around the tumor, thereby increasing the likelihood of pulmonary hemorrhage. Li et al. [23] suggested that the smaller the diameter of a pulmonary nodule, the higher the probability of pulmonary hemorrhage. This is thought to be because smaller nodules are more difficult to puncture, requiring constant adjustment of the needle tip during the procedure, which results in greater damage to lung tissue and blood vessels, thereby increasing the likelihood of pulmonary hemorrhage. Other literature suggests [7] that risk factors for pulmonary hemorrhage include serum platelet count and tumor size, which are related to the patient's baseline coagulation function. Patients with inherently low platelet counts, hematological disorders, or those on long-term oral anticoagulants naturally face an increased risk of pulmonary hemorrhage.

For patients with blood-streaked sputum or minor hemoptysis, administer cough suppressants and instruct them to lie on their affected side; no special treatment is required. For patients with moderate hemoptysis, administer intravenous hemostatic agents and

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posterior pituitary hormone, while continuously monitoring respiration, blood pressure, and oxygen saturation, and closely observing the patient’s vital signs. For patients with massive hemoptysis or even hemorrhagic shock, high-flow oxygen therapy should be administered, and hemostatic and volume-expanding agents should be rapidly infused. If necessary, interventional bronchial artery embolization or surgical treatment should be performed. In cases of acute respiratory failure, immediate endotracheal intubation or tracheostomy should be performed. To reduce the incidence of pulmonary hemorrhage, the operator should avoid the intercostal and intrathoracic arteries during the ablation procedure, use coaxial puncture to minimize the number of punctures, and closely monitor the patient’s vital signs postoperatively. In particular, for patients with low platelet counts or those undergoing cryoablation, the observation period should be extended.

5. PAIN

Pain is the most common symptomatic complication during and after CT-guided ablation of pulmonary nodules. Its incidence reaches nearly 100% [24]. Almost every patient feels pain.Pain can be categorized into acute intraoperative pain, short-term postoperative pain, and chronic postoperative chest pain, and can be classified into three levels—mild, moderate, and severe—based on its intensity. Most cases involve mild to moderate pain, though a small number of patients may experience moderate to severe pain, leading to interruption of the ablation procedure and a decline in postoperative quality of life. A study on the symptomatic experience of elderly patients following microwave ablation [25] found that some elderly patients also develop psychological issues such as anxiety and insomnia due to pain, and may continue to experience pain even after a period of postoperative recovery. Pain caused by thermal ablation of pulmonary nodules is primarily associated with thermal stimulation and damage to the target area and surrounding nerves due to high temperatures. Larger intralungary vessels and bronchi contain pain-sensing nerves, whereas the visceral sensory fibers innervating the lungs are few in number, thin in diameter, and have a high pain threshold. The visceral pleura is primarily innervated by the autonomic nervous system and does not respond directly to cold or heat stimuli, whereas the parietal pleura is innervated by the intercostal and phrenic nerves and is highly sensitive to mechanical and thermal stimuli, with clear localization of pain [26]. Pain caused by cryoablation is typically milder because the nerve damage is reversible and the procedure has a local anesthetic effect, resulting in generally milder postoperative pain [27]. During thermal ablation of pulmonary nodules, if the lesion is too close to the pleura, the heat may damage the intercostal nerves, resulting in radiating pain along the distribution of these nerves. This pain may feel burning or stabbing, worsen with coughing or deep breathing, and may be accompanied by sensory abnormalities and numbness in the corresponding dermatomes. Intraoperative pain is often characterized by a sharp, stabbing pain or a burning sensation, occurring at the moment of puncture or during the ablation process. Some patients describe it as a sensation of “the chest wall being burned.” When the phrenic nerve is damaged, the pain may radiate to the same-side shoulder or back. Postoperative pain is typically dull or aching and lasts from several hours to several days.

A study by Tomohisa Okuma et al. on radiofrequency ablation of lung tumors [28] found that lesions located within 1 cm of the chest wall were significantly associated with pain and constituted an independent risk factor for its occurrence. A study by Wang Lina et al.[29] used multivariate logistic regression analysis to conclude that the distance of the lesion from the pleura, puncture depth too shallow, and the use of multi-needle ablation—these three factors—significantly increased the risk of pain during pulmonary microwave ablation.

Accurately understanding the degree of patients' pain is more conducive to our treatment and prevention of this common complication. At present, the tools commonly used to evaluate the pain caused by thermal ablation include numerical rating scale (NRS) and visual analogue scale (VAS)[30]. Some other researchers improve the VAS pain scoring method. They take patients' pain intensity during thermal ablation and tolerable ablation duration as main scoring indicators [31]. Ablation for lung tumors may trigger pain. Clinicians adopt multiple ways to prevent this pain comprehensively. They use analgesic and sedative drugs, local pleural anesthesia and intentional pneumothorax. Besides, the application of non-invasive temperature measurement technology in ablation is also expected to reduce the incidence of pain caused by thermal ablation [32].We cannot ignore another important measure. It is necessary to fully communicate with patients before ablation, explain possible pain and coping styles, and reduce patients' anxiety and fear.

6. SUMMARY

CT-guided lung nodule ablation is a safe and effective minimally invasive treatment option that offers an important alternative for patients with lung nodules who cannot tolerate surgical procedures. However, four complications—pneumothorax, pleural effusion, bleeding, and pain—remain key factors affecting treatment safety, patient prognosis, and patient experience. The prevention and management of these complications must adhere to the core principles of precise preoperative assessment, standardized intraoperative procedures, early postoperative identification and diagnosis, and stratified, individualized management. In the future, we hope to further advance ablation techniques, refine surgical procedures, and explore more effective preventive interventions to reduce the incidence of complications. This will help promote the development of CT-guided lung nodule ablation toward greater standardization, precision, and safety, thereby better serving clinical practice and patient health.

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