JBR–BTR, 2013, 96: 142-154.

# PERCUTANEOUS ABLATION OF MALIGNANT THORACIC TUMORS*

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**Lung cancer is the leading cause of death related to cancer. Fifteen to thirty percent of patients with a localized lung cancer are actually inoperable as they present with poor general condition, limited cardiopulmonary function, or a too high surgical risk. Therefore, minimally invasive treatments are needed and percutaneous ablation seems an attractive option. Thermal ablation can be performed by delivering heat (radiofrequency, microwave, laser) or cold (cryotherapy) through a needle inserted into the tumor under CT guidance. The ideal lesion is less than 2 or 3 cm in diameter. Success of percutaneous thermal ablation appears to be close to those of surgery for localized lung cancer. Nevertheless studies are still needed to definitely assess the role of ablation compared to other emerging techniques, as stereotactic radiotherapy as well as potential synergy with other treatments.**

**Key-word: Lung neoplasms, therapy.**

Lung cancer is the leading cause of death related to cancer and accounted for 29% of cancer deaths in the U.S. in 2009 (1). Eighty percent of lung cancers are non-small cell lung cancer-type (NSCLC). Surgical treatment combining lobectomy or pneumonectomy and hilar and/or mediastinal lymphadenectomy remains the only proven curative treatment of stage I-II NSCLC. However, 15-30% of patients may not benefit from surgery, most often due to poor general condition, comorbid cardiopulmonary disease as insufficient pulmonary reserve, or a high surgical risk (1-5).

The lungs are the second most frequent site of metastases of extrapulmonary cancers after the lymphatic system. The lungs are the only site of metastasis in approximately 20% of patients after resection of the primitive neoplastic lesion. When the number of lung metastases is limited, their surgical resection is associated with improved survival (1). Unfortunately, as the same exclusion criteria for surgery mentioned above also apply, alternative therapies must be considered, including external beam radiation therapy with or without chemotherapy, improving modestly survival, often with significant toxicity to the patient (2, 3).

Therefore, minimally invasive treatments are needed and percutaneous ablation seems an attractive option. After preliminary studies on the electrochemical polarization of cancers, new percutaneous therapeutic modalities have emerged, including percutaneous brachytherapy (6) and thermal ablation of tumors by radiofrequency (RF) or other sources of energy (7). Thermal ablation is currently used to treat focal malignant lesions located in the liver, kidney, breast, thyroid, head and neck, chest and bones, acting as a substitute or adjunct to other therapeutic modalities (8). Percutaneous thermal ablation is a technique that seems particularly well suited to treat lung tumors, the insulating effect of air in normal lung tissue surrounding the lesion acting like an oven by concentrating the heat in the target tumor (9). Therefore, for a given level of energy, the ablation volume is wider in the lung than in other soft tissues. Moreover, the normal lung parenchyma heals quickly after a thermal injury, and damage to surrounding healthy lung is consequently minimal (9). Theoretically, the main advantages of percutaneous thermal ablation techniques include: relative sparing of healthy tissue which is important to treat patients with reduced cardiopulmonary reserve, reduced morbidity and mortality, faster recovery and earlier discharge from hospital, lower cost, possibility of outpatient treatment, potential synergy with other treatments, and possibility to repeat ablation sessions on the same lesion (10).

## Types of energy

Thermal ablation of tumors located in the lung, chest wall, pleura or mediastinum has been safely performed under CT guidance, mainly with the RF energy so far. Other energy sources are available, including microwave, cryoablation and laser (2, 7, 10, 11). The type of energy that can be used will depend on the patient, location and nature of the tumor, treatment goal, and operator experience or preference.

### *Radiofrequency*

The RF energy used in tissue ablation is a sinusoidal current from 400 to 500 kHz issued by an electrode/needle positioned in the target lesion. The RF ablation (RFA) probe acts as the cathode of an electrical circuit that is closed by dispersive electrodes applied on the patient's thighs (unipolar system). On a few millimeters around the needle, the ionic agitation resulting from the alternating current produces a resistive heating by friction between the molecules. The heat is then transmitted by thermal conduction to the surrounding tissues, causing coagulation necrosis within 1 to 2 cm. The goal is to increase tissue temperature between 50 and 100°C for 4-6 minutes, which is sufficient to cause irreversible cell damage. In contrast, temperature above 105°C causes boiling, vaporization and carbonization of tissue which, by increasing the impedance, decrease the transmission of energy and thereby the size of the ablated area. Therefore manufacturers had to commercialize various types of RFA devices to overcome this limitation and to increase the size of the ablation zone. Some needle designs allow deployment of the tip into multiple electrodes in a "umbrella" – or "bouquet of flowers" – like mode, allowing a larger volume of thermal injury, which can reach up to 5 cm in diameter (8) (Fig. 1). Other devices or technical algorithms allowing larger thermal injury have also been developed, including needles having an internal cooling and allowing RF energy administration without reaching 100°C in contact of the needle, pulsed RF energy administration, or injection of saline into the lesion (3, 8) (Fig. 1, 2). When treating a large lesion, it may be necessary to use multiple needles, which had to be activated sequentially rather than

*Meeting "Lung Cancer Imaging in 2012: Updates and innovations", Tervuren, 10.11.2012.
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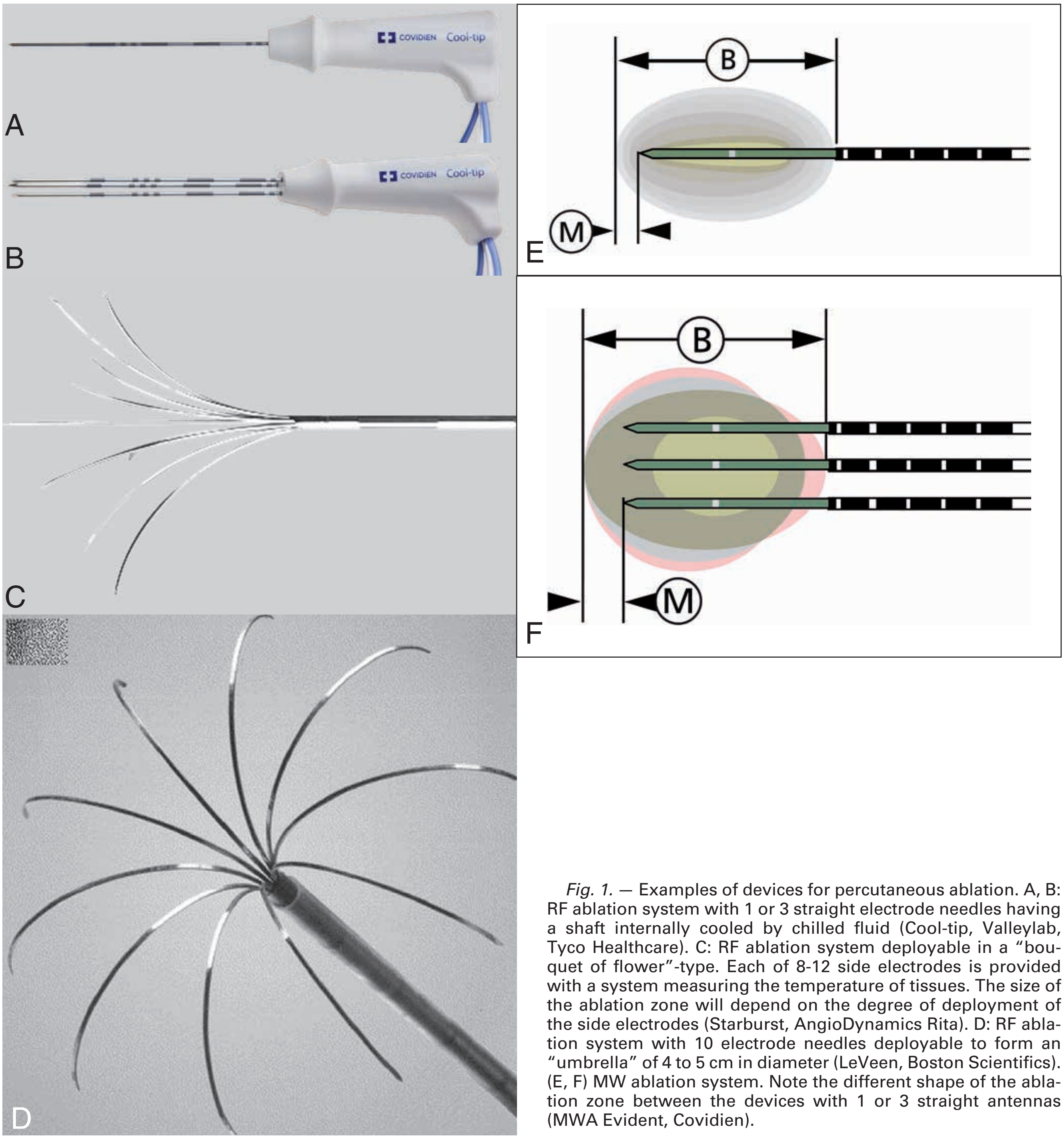



*Fig. 1.* — Examples of devices for percutaneous ablation. A, B: RF ablation system with 1 or 3 straight electrode needles having a shaft internally cooled by chilled fluid (Cool-tip, Valleylab, Tyco Healthcare). C: RF ablation system deployable in a "bouquet of flower"-type. Each of 8-12 side electrodes is provided with a system measuring the temperature of tissues. The size of the ablation zone will depend on the degree of deployment of the side electrodes (Starburst, AngioDynamics Rita). D: RF ablation system with 10 electrode needles deployable to form an "umbrella" of 4 to 5 cm in diameter (LeVeen, Boston Scientifics). (E, F) MW ablation system. Note the different shape of the ablation zone between the devices with 1 or 3 straight antennas (MWA Evident, Covidien).

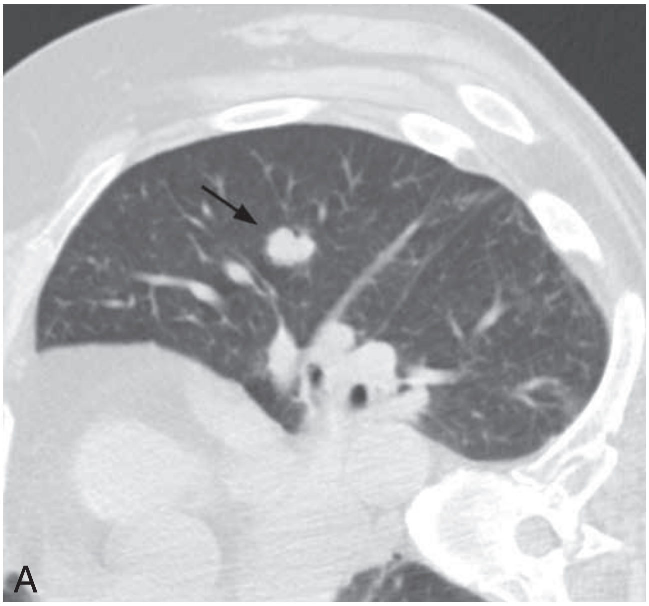
simultaneously, or to reposition sequentially a single needle to encompass treatment of the whole lesion.

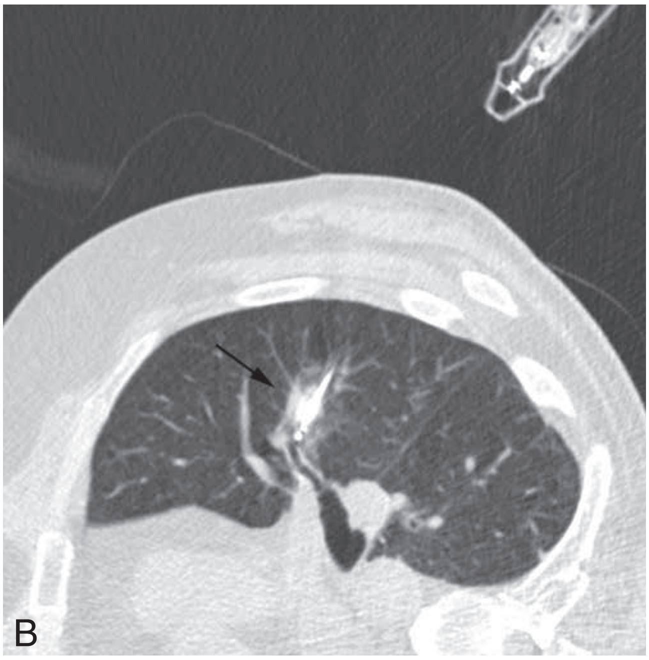
While hypoxia and low blood flow in the center of a necrotic tumor generally render cells more resistant to radiotherapy and chemotherapy on the one hand, they are responsible for a greater sensitivity to RFA on the other hand, as the dissipation of heat is decreased (12, 13). At the opposite, the presence of vessels around the lesion, particularly when larger than 3 mm in diameter, or of large caliber bronchi of more than 2 cm, is responsible for local heat dissipation by thermal conductivity (this is called the "*heat-sink effect*") that may cause persistence of non-ablated tissue and treatment failure (Fig. 3).

Patients having pacemaker/defibrillator, or other metallic implants should not be treated with RFA, although this type of energy can theoretically be applied if the implanted device is controlled by a cardiologist (14, 15). Bipolar systems having two active electrodes inserted into the lesion are now commercially available, overcoming the need for dispersive skin electrodes.

### *Microwave*

Thermal ablation by microwave (MW) is a more recent technique using an electromagnetic energy from 900 to 2450 MHz frequencies that increases the temperature of tissue by stirring the molecules of water (10)



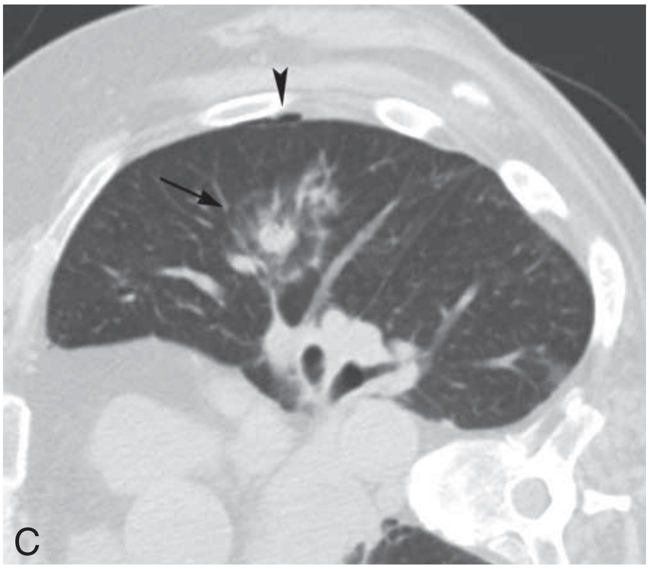




*Fig. 2.* — Radiofrequency ablation. A: Preablation CT image shows a 14 mm squamous cell lung carcinoma (arrow) in the left upper lobe. B: Perprocedure CT image shows a single straight Cool-tip needle transfixing the lesion (arrow). C: Control CT image obtained at the end of the procedure shows a slight ground-glass halo (arrow) of 10 mm thickness around the lesion. Note also a small pneumothorax (arrowhead).

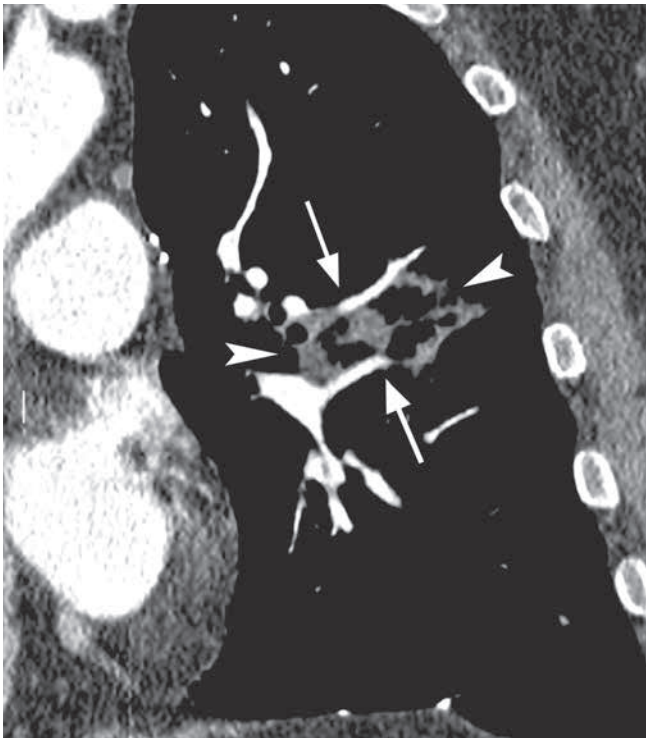
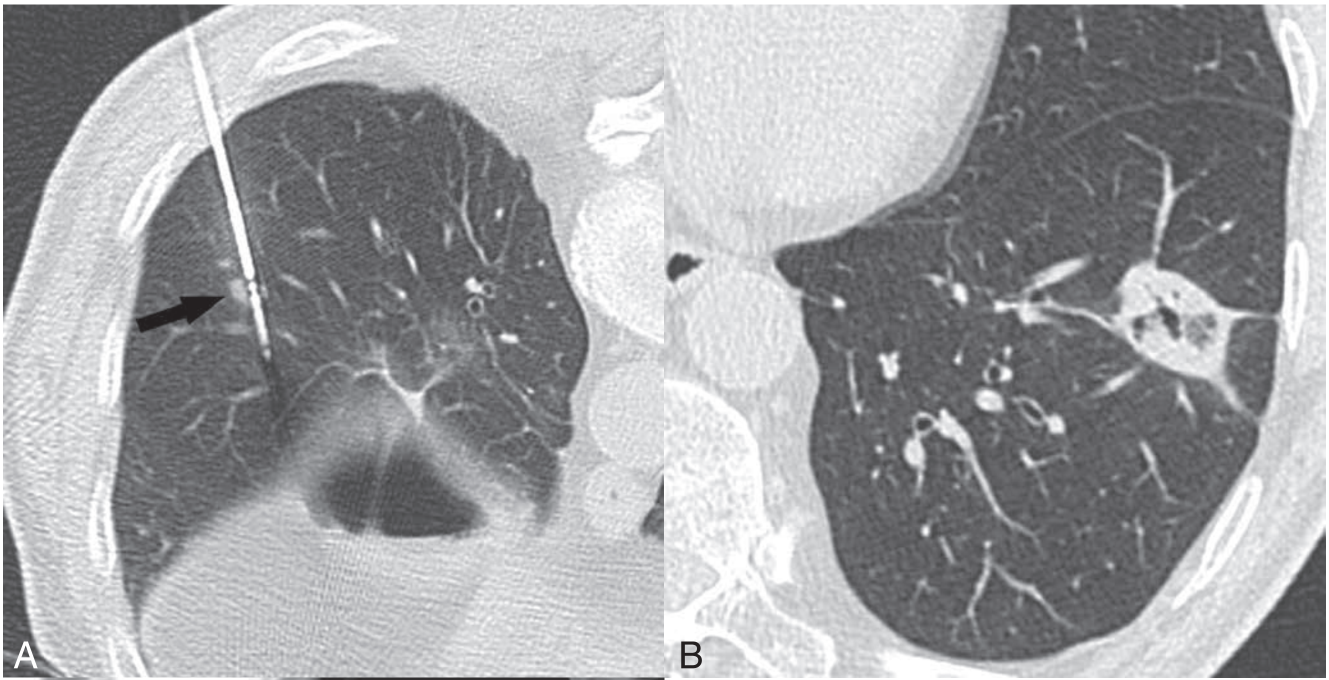


*Fig. 3.* — Heat-sink effect. Squamous cell lung carcinoma in the left upper lobe treated with RFA using a Cool-tip needle. Coronal reformat in mediastinal window shows that the margins of ablation are oval in shape. Safety margins at the upper and lower portions of the lesion (long arrows) are flattened and thinner when compared to the internal and lateral margins (arrowheads). This is due to the presence of vessels above and below the lesion, that are responsible for heat loss (heat-sink effect) and potentially resulting in incomplete ablation in those areas.

(Fig. 4). The electromagnetic nature of the MW overcomes the problems due to impedance increase secondary to tissue carbonization that may be observed with RFA, and results in a larger ablation volume and safety margins (16). MW ablation (MWA) is therefore less sensitive to the *heat-sink effect* than RFA, as higher temperature can be reached (up to 150°C), but this may be associated with an increased risk of vascular thrombosis (17). Other advantages of MWA are faster rise of temperature, a more spherical pattern of ablation, ability to activate multiple antennas simultaneously, reduced procedure time, no risk of skin burn on the thighs (no dispersion electrode)



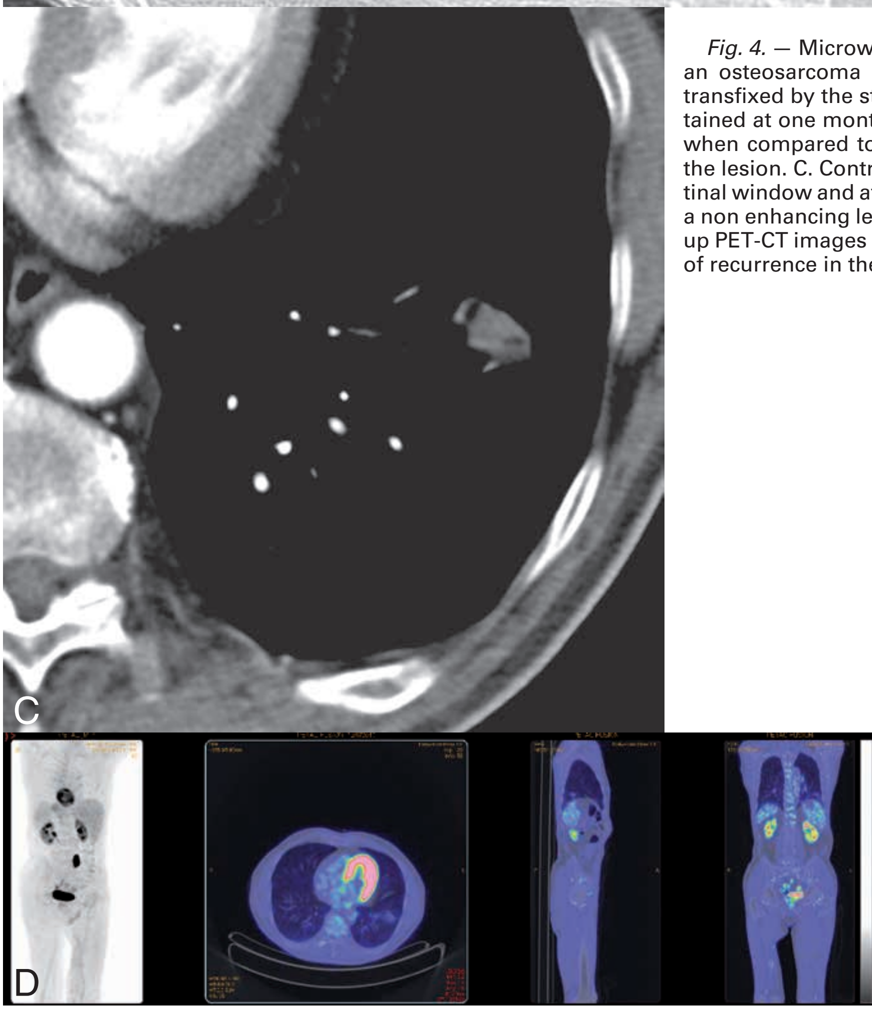


*Fig. 4.* — Microwave ablation. Left lower lobe metastasis from an osteosarcoma of the lower limb. A: The lesion (arrow) is transfixed by the straight MW antenna. B: Control CT image obtained at one month after ablation shows a larger thermolesion when compared to (a). Note small bubble-like lucencies inside the lesion. C. Control CT image obtained at 3 months in mediastinal window and after IV contrast medium administration shows a non enhancing lesion that is smaller compared to B. D. Follow-up PET-CT images at 6 months show no FDG uptake and no sign of recurrence in the ablation area.

and less pain when tumor is in contact or located in the chest wall. There is also no interference with electromagnetic waves used in MRI, allowing real-time monitoring of treatment efficacy under MR. Interference with pacemakers/defibrillators are also less important provided that the treatment area is more than 5 cm away from the heart.

MWA would therefore be an ideal technique in case of lesion that is more than 4 cm in diameter, in contact with vessels larger than 3 mm in diameter, in patients with limited respiratory function, or in case of recurrence after thermal ablation performed by another type of energy (18).

*Cryoablation*

Cryoablation is tissue ablation using cold, a temperature drop of at least -20 to -25°C being lethal for tissues. Cryoablation provides a wide ablation zone in a short time, through various direct and indirect mechanisms, including protein denaturation, breakdown of extra-and intracellular membranes, and ischemia. The treatment can be monitored in real time under US, CT or MR, through visualization of the ice ball whose outer boundary corresponds to the 0°C isotherm, while the isotherm -20°C is located approximately 5 mm inside the latter (19). However, whereas the ice ball is clearly identifiable in the chest wall or mediastinum on CT, it may be less visible in the lung parenchyma because of the

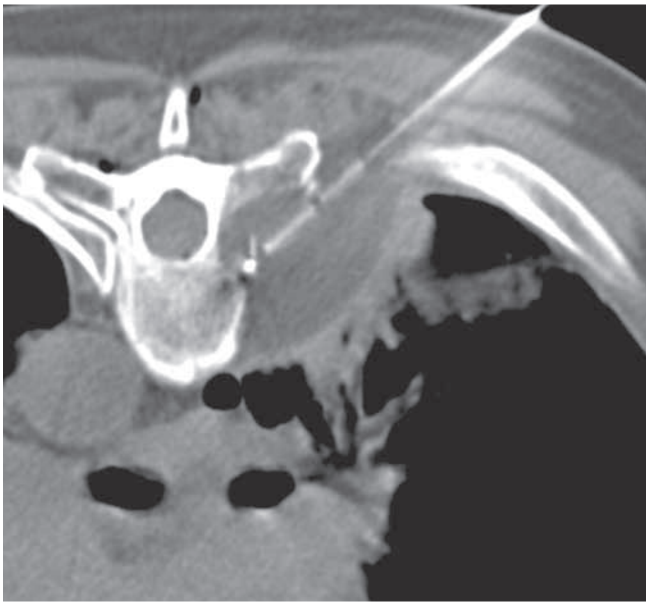


*Fig. 5.* — Cryoablation. Cryoablation of a painful metastasis invading the chest wall. The margins of the oval ice ball are perfectly delineated allowing to check the proper covering of the tumor and to control the safety gap with adjacent vulnerable tissues, including the spinal cord. For optimal thermal protection of the spinal cord, thermosensors were inserted into the foramina and insulation of the spinal canal was achieved with epidural CO2 dissection (not shown). Courtesy from Afshin Gangi, University Hospital of Strasbourg, France.

low density of air around the thermolesion (Fig. 5). The anesthetic effect of cold on tissues and nerves is a prominent advantage, making the technique particularly suitable for the treatment of lesions located in the chest wall or close to the pleura (11). Finally, the associated antitumoral immune response would be more important than for other ablation techniques, and preservation of tissue architecture allows better cellular repopulation of healthy peritumoral tissues. However, cryoablation carries an increased risk of bleeding, because it has no cauterization effect on the vessels. When frozen, a lesion is more susceptible to trauma and can fracture. The increased risk of bleeding must be considered in patients with precarious lung function (20). Similar to the *heat-sink effect* for RF, the technique is susceptible to a *cold-sink effect* by blood flow through vessels larger than 3 mm in diameter. Though the experience is still limited in the thorax, cryoablation seems a safe technique in case of parietal lesion or peripheral pulmonary lesion (21).

*Laser*

Laser interstitial thermotherapy (LITT) delivers a high energy laser radiation (Nd:YAG laser) into the tumor via optical fibers. The tip of the fibers is terminated by a diffuser that emits laser light on an effective distance of 12 to 15 mm (17). Since heat diffuses slowly towards the periphery of the lesion, an exposure time of 10 to 30 minutes is required, depending on the size of the lesion, to obtain a sufficiently high temperature to induce a coagulation necrosis. The technique is not currently widely used in the thorax despite reported results close to ablation with other types of energy, probably because of the complexity of the procedure and the higher caliber of the material. The main advantages of LITT versus RFA are the independence from tissue impedance, the possibility to monitor the procedure in real time under MR, and less aggression to surrounding tissues.

*Others*

Irreversible electroporation is a new non-thermal ablation technique, creating permanent pores in cell membranes, leading to cellular deregulation and apoptosis. It uses a high voltage electric current, requiring general anesthesia and cardiac monitoring. The application of this technique in the lung is still preliminary (22). Advantages over other ablation techniques would be absence of sensitivity to the *heat-sink effect*, a shorter treatment time and less fibrous scarring (23).

High intensity focused ultrasounds are another ablation technique, but not used in the thorax so far.

## Indications

The therapeutic approach to any tumoral lesion must be discussed in multidisciplinary oncologic meetings, the respective roles of each therapy evolving continually according to their own progress. It is important to emphasize that, similar to surgery, ablation provides only a local control of the disease. The main indications for ablation are stage I or II NSCLC and recurrent or limited pulmonary metastatic disease in patients that are inoperable or refuse surgery. In case of NSCLC, surgery should always be offered as first-line, lobectomy with lymph node revision being superior to sub-lobar resection and therefore *ipso facto* to percutaneous ablation (3). Regarding metastasis, nature of the primary cancer and its local control are important factors to consider. Thus, as for surgery, metastatic colorectal cancer and sarcoma are among the most suited conditions for ablation. The maximal number of metastasis that can be ablated is not strictly defined, varying from three to six according to the majority of the authors.

The *ideal* target lesion for ablation is a lesion measuring less than 3 cm diameter, and not in contact with large vessels or bronchi, mediastinum and chest wall (2, 13, 24-30).

More uncommon indications are reported in the literature, including palliation of symptoms such as pain, cough or hemoptysis, recurrent disease in a radiation field, or tumor debulking (2, 3, 14, 28, 31-34) (Fig. 5).

## Contraindications

The contraindications are basically the same as for percutaneous transthoracic biopsy (PTTB). Coagulation disorders must absolutely be controlled. Severely reduced pulmonary reserve ($FEV_1 < 0.6$ L), single lung or pulmonary hypertension are not absolute contraindications (3, 35) (Fig. 6). General anesthesia or deep conscious sedation can solve problems in non-cooperative patients or patients presenting with intractable cough. An acute pneumonia in contact with the tumor must

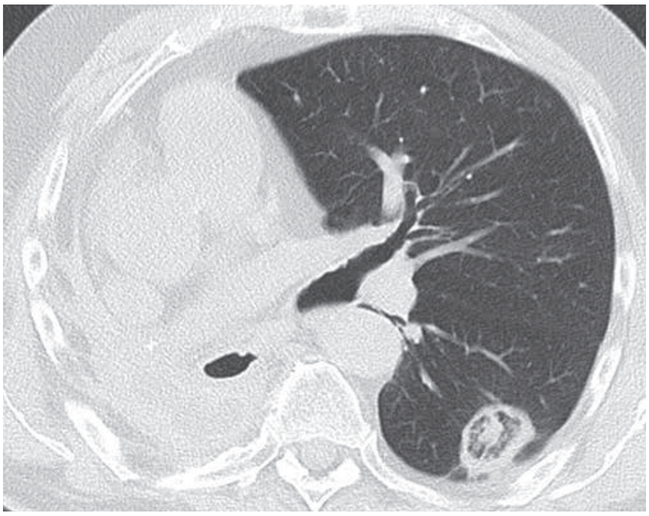


*Fig. 6.* — Tumor ablation in a patient with single lung. MW ablation of a 7 mm squamous cell carcinoma in left lower lobe in a patient who underwent right pneumonectomy for stage IIIa NSCLC several years earlier. Follow-up CT image at 1 month after the procedure shows a target pattern of the thermolesion, showing from center to periphery: the ghost of the tumor, a halo of ground glass representing the safety margins of ablation, and a dense rim of inflammatory tissue. There was neither complication nor recurrence of the treated lesion at follow-up.

be treated before ablation in order to prevent the spread of the thermal injury to non-tumoral lung (2). Ideally, patients with pacemakers / pacemaker should better be treated with cryoablation or MW, which have less interferences than RF on these devices.

**Procedure**

Confirmation of the tumoral nature of the target lesion should be obtained before planning the procedure. Whatever the type of energy used, the procedure is usually performed under conscious sedation or general anesthesia, depending on the patient, type of lesion and the choice or experience of the operator (10, 11, 19). At the minimum, the patient is put under oxygen administration with continuous monitoring of cardiorespiratory parameters. When using RF, a minimum of two dispersive electrodes are carefully pasted on the thighs. The parietal pleura is anesthetized and systemic analgesics are administered, as thermal ablation of parietal lesions or close to the pleura can be painful during or after the procedure. When treating a lung tumor close to the pleura, an artificial pneumothorax can be obtained to reduce the pain (36) (Fig. 7).

Precautions, technical ease and procedure of the needle/antenna placement are similar to those of PTTB (37). When multiple needles are needed to treat the whole lesion, they should all be correctly positioned in the target before applying any power to any needle. Their precise deployment is greatly facilitated by the use of fluoro-CT, and optimal positioning relative to the lesion and non-target organs should be confirmed by MPR views (38).

Duration and number of treatment applications depend first on the type of energy system used, and secondly on the size and morphology of the target lesion. The shape of each ablation zone is specific to each device and is generally oval in the axis or perpendicular to the axis of the needle. The criteria for treatment success vary from one system to another, some being based on an abrupt increase of impedance (roll-off), while others are based on the intratumoral temperature (70°C ideally). Similar to surgical margins, it is of utmost important to ablate an area of healthy tissue around the lesion. Systematic margins of 0.8 to 1.0 cm are recommended since microscopic extension around of the lesion cannot be predicted based on CT images. Those margins appear as a rim of ground-glass that corresponds to the combination of coagulation necrosis, inflammation, congestion and pulmonary hemorrhage (Fig. 2, 3, 6, 7 and 8). This rim should be correctly identified in all three dimensions (Fig. 3 and 8). Studies have reported more than 80% of treatment failure when the rim of ground-glass was not identified on control CT (39, 40). When the total area of the thermal injury is four times that of the tumor, the success rate of complete necrosis is 96% whereas it falls to 80% if this proportion is not reached (41). Similarly, when the ablation volume is more than three times the tumor volume, tumor destruction is complete in 83% against 61% when this proportion is not reached (27).

If the lesion is in contact or near the mediastinum, particularly when close to vascular structures, a *heat-sink effect* can occur. Contact with vessels larger than 3 mm or large caliber bronchi should encourage the use of MW or cryoablation that are less sensitive to *heat-sink effect* than RF. When necessary, an iatrogenic pneumothorax can be created to separate the tumor from the heart or great vessels. On the other hand, esophagus, trachea and nerves (mediastinal and parietal, particularly the brachial plexus) are sensitive to thermal ablation, and hydrodissection using glucose fluid or CO2 dissection can be performed to isolate the sensitive structures from the heat source.

Finally, skin tissue at the puncture site should always be controlled, as they are also sensitive to thermal damage. When treating a superficial lesion, mechanisms of local cooling or heating depending on the type of energy should be used to protect them.

At the end of treatment, some devices allow a cauterization of the intrapulmonary needle tract to reduce the risk of bleeding, pneumothorax, and especially of tumor dissemination.

The patient is monitored afterwards in the recovery room. A chest radiograph is obtained 2 to 4 hours after the intervention. Painkillers will be administered on demand, and anti-inflammatory drugs are often administrated to prevent the post-ablation syndrome. Prophylactic administration of antibiotics is controversial. Depending on the type of anesthesia, patients are discharged from hospital either on the same day, either 24 or 48 hours later.

**Results**

*Primary tumors*

Complete ablation rate was around 90% in a review of the literature

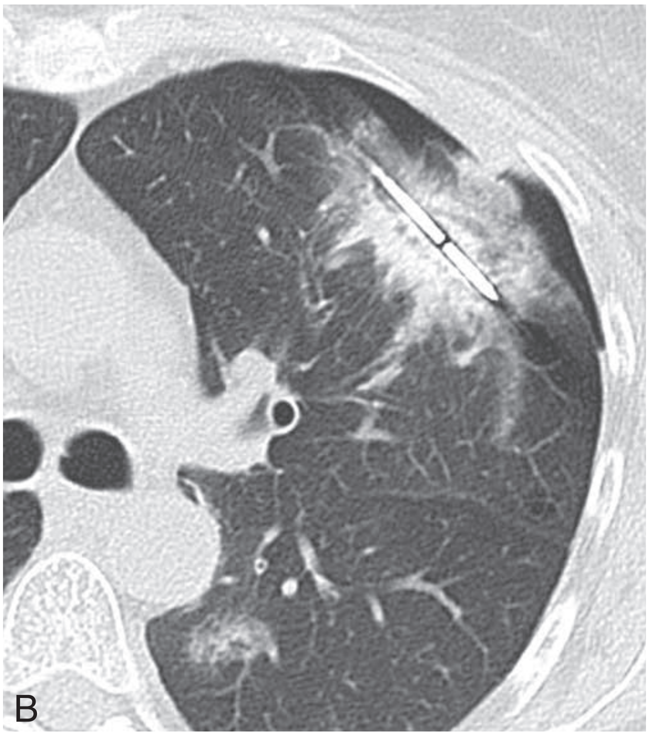


*Fig. 7.* — Sensitive structures isolation. A: Preablation CT image shows a 15 mm adenocarcinoma (arrow) close to the pleura in the left upper lobe. B: Apparition of a self-limited pneumothorax after insertion of the MW antenna. This iatrogenic complication had the benefit of holding the site of ablation off the sensitive parietal pleura and chest wall, and thus protecting against per- and post-procedural pain. Note ground-glass halo surrounding the treated lesion. C: Control CT image obtained at 3 months shows a smaller and denser lesion compared to B, also showing more angular contours. Note a small cavitation in the right part and aerated ghost path positions of the MW antenna in the left part of the lesion.

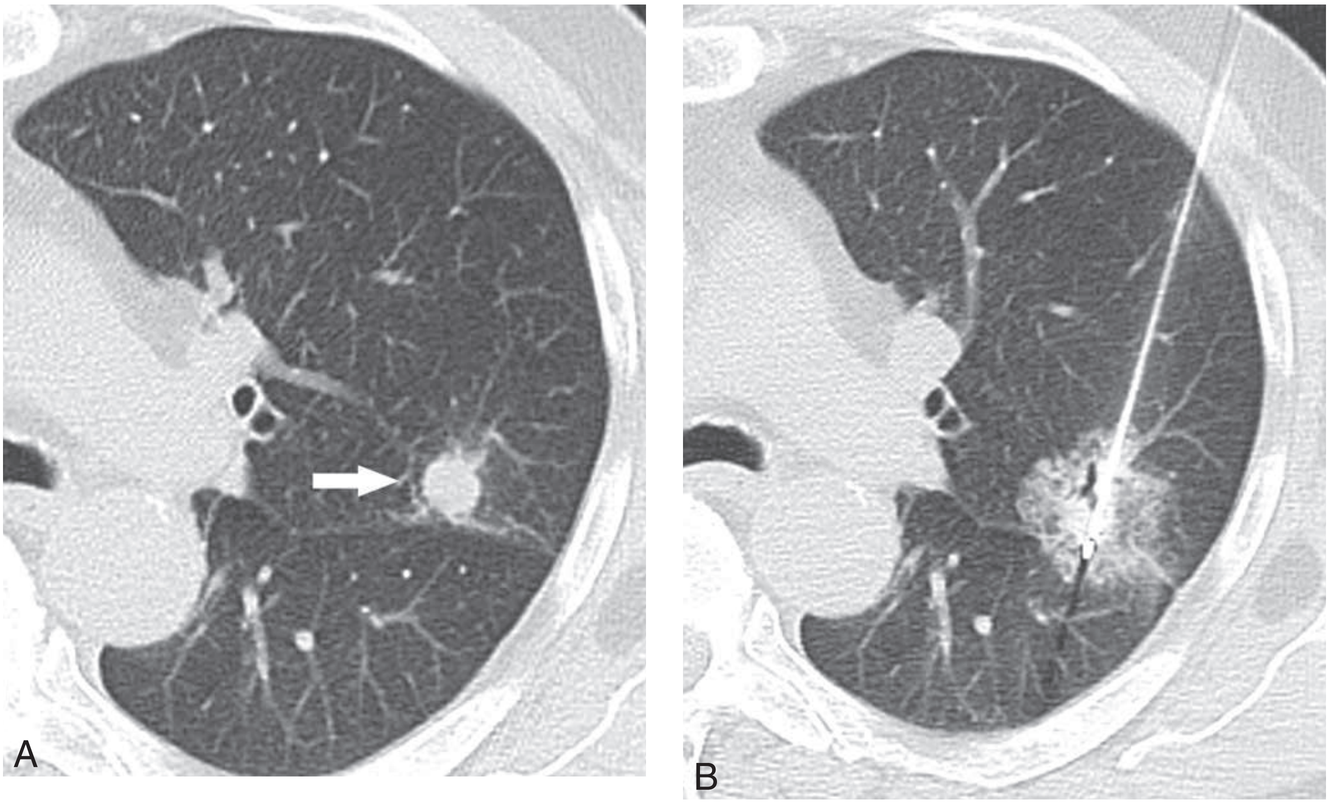
including 17 series (4). Comparison of results across studies is difficult due to the heterogeneity of populations, tumor characteristics, ablation techniques and devices (ablation alone or combined with chemotherapy), and lack of standardization of response criteria and monitoring. Most studies show a significantly inferior rate of complete ablation when the tumor exceeds 2 or 3 cm in diameter (2, 3, 13, 24-30, 41, 42).

Survival data after ablation are not yet mature, the technique still being too recent. Surgery is the treatment of choice for stage I and II NSCLC with a survival rate of 75% and 50%, respectively. Early results of percutaneous ablation treatment of stage I and II NSCLC appear to be close to those of surgery, keeping in mind that the majority of the treated patients presents with contraindications to surgery (Table I).

*Pulmonary metastases*

After surgical resection, survival of patients with pulmonary metastases is 36, 26 and 22% at 5 years, 10 years and 15 years, respectively. In case of incomplete resection, survival drops to 13 and 7% at 5 and 10 years, respectively (43). After percutaneous ablation of pulmonary metastatic lesions, the survival is 64 to 78% at 2 years and 27 to 57% at 5 years (26, 29, 30, 41, 44) (Table II). Results are significantly higher in case of combined ablation / chemotherapy than chemotherapy alone (87 versus 33%) (45).

The overall results of percutaneous ablation are difficult to compare with those of other therapies, particularly surgery, due to differences in patient population. Indeed, the vast



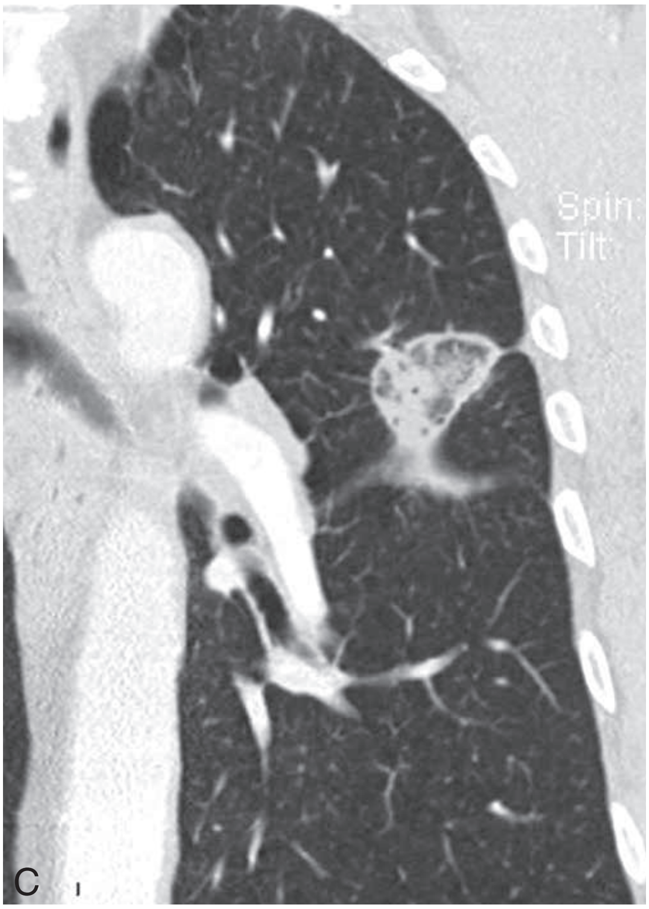




*Fig. 8.* — Radiofrequency ablation. A. Preablation CT image shows a 12 mm adenocarcinoma (arrow) close to the fissure in the left upper lobe. B. Perprocedure CT image shows a halo of ground-glass thicker than 8 mm surrounding the treated lesion, indicating probable complete necrosis of the lesion. C: Follow-up CT coronal reformat shows the target-pattern of the ablated zone. Such aspect has to be demonstrated in all 3 dimensions to ensure successful treatment of the lesion.

majority of patients treated with ablation have contraindications to other treatments, which makes the results of ablative therapy even more encouraging. Repeated ablations improve local control in patients showing a persistence of viable tumor tissue (2, 25, 46).

After ablation, cancer-related survival is the order of 83-93% at 1 year, 68-75% at 2 years and 59-61% at 3 years (25, 47, 48). Prospective controlled studies are still needed to definitely assess the role of ablation.

Studies are also needed to investigate the theoretical synergistic effects of combining percutaneous ablation and radiotherapy, including stereotactic radiotherapy (42, 49). For stage I and II tumor, the first studies of such combined treatments reported a survival of 87, 70 and 57% at 1, 2 and 3 years, respectively, that may be superior than after percutaneous ablation alone (2, 13, 28). The addition of chemotherapy to percutaneous ablation seems also to increase survival in patients with NSCLC.

**Complications**

Percutaneous ablation procedures are well tolerated in the hands of an experienced operator. Complications are usually minor and major

*Table I. — Percutaneous ablation of NSCLC.*

| | | | Patients | Lesions | Mean size (cm) | Global survival (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 y | 2 y | 3 y | 4 y | 5 y |
| Akeboshi (24) | 2004 | RF | 10 | 13 | 2,7 ± 1,3 | 89 | | | | |
| Grieco (13) | 2006 | RF* | 37 | | | 87 | 70 | 57 | | |
| De Baère (41) | 2006 | RF | 9 | 9 | | | 76 (18 months) | | | |
| Simon (28) | 2007 | RF | 75 | 80 | 2,7 | 78 | 57 | 36 | 27 | 27 |
| Pennathur (61) | 2007 | RF | 19 | | 2,6 | 95 | 68 | | | |
| Hiraki (62) | 2007 | RF | 20 | | 2,4 | 90 | | 74 | | |
| Lencioni (47) | 2008 | RF | 33 | | 1,7 | 70 | 48 | | | |
| Wolf** (48) | 2008 | MW | 50 | 82 | 3,5 ± 1,6 | 65 | 55 | 45 | | |
| Lanuti (42) | 2009 | RF | 31 | 34 | 2 | 85 | 78 | 47 | | |
| Ambrogi (25) | 2011 | RF | 57 | 59 | 2,6 | 83 | 62 | 40 | | 25 |

* + Radiotherapy.
** Includes NSCLC and metastases.

*Table II. — Percutaneous ablation of lung metastases.*

| | | | Patients | Lesions | Mean size (cm) | Global survival (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 y | 2 y | 3 y | 4 y | 5 y |
| Akeboshi (24) | 2004 | RF | 21 | 41 | 2,7 ± 1,3 | 84 | | | | |
| Yan (30) | 2006 | RF | 55 | | 2,1 ± 1,1 | 85 | 64 | 46 | | |
| De Baère* (41) | 2006 | RF | 51 | 91 | 1,7 ± 0,9 | | 71 (18 months) | | | |
| Simon (28) | 2007 | RF | 18 | 28 | 2,7 | 87 | 78 | 57 | 57 | 57 |
| Yamakado (29) | 2007 | RF | 71 | 155 | 2,4 ± 1,3 | 84 | 62 | 46 | | |
| Wolf** (48) | 2008 | MW | 50 | 82 | 3,5 ± 1,6 | 65 | 55 | 45 | | |
| Lencioni (47) | 2008 | RF | 73 | 150 | 1,7 | 89-92 | 64-66 | | | |
| Gilliams (26) | 2008 | RF | 37 | 72 | 1,8 | | | | | |
| Rosenberg (44) | 2009 | LITT | 64 | 108 | 2 | 81 | 59 | 44 | 44 | 27 |
| Pallusière** (56) | 2011 | RF | 189 | 350 | 1,5 | | 72 | 60 | 51 | |

* Includes nine patients with NSCLC.
** Includes NSCLC and metastases.

complication rate is seen in less than 10% (3, 50, 37). A mortality rate from 0.4 to 2.6% is reported, most often due to bleeding, pulmonary sepsis, ARDS, heart failure, or pulmonary embolism (4, 28, 40, 50).

Although the procedure is well tolerated, the patient may present with mild to moderate pain ([2, 38). Cryotherapy has the advantage of being less painful than the techniques using heat when treating peripheral or parietal lesions.

Pneumothorax is the most common minor complication (10-50%) (Fig. 2, 7 and 9). Risk factors and prevention are similar to those of PTTB. The rate of chest drainage is also similar to that reported after PTTB (10-30%) (3, 40).

Post-ablation syndrome, presenting with fever, cough, chills, vomiting and malaise, is reported in up to one third of cases and may last from 1 to 7 days. Treatment is strictly symptomatic. The need for prophylactic antibiotics administrated just before the intervention and during the next 5 days is still controversial. Some authors recommend it particularly in patients with prosthetic heart valve or artificial joints (21). Pneumonia is reported in up to 22% of cases, most often in cases of tumor in a central location, associated with retro-obstructive pneumonia, or in case of underlying chronic lung disease (3, 21).

Intraparenchymal hemorrhage is uncommon and more generally due to the manipulation of the needle than the thermal ablation itself, since it has a cauterizing effect (with the exception of cryotherapy). Minor hemoptysis is reported in 15% of cases; major bleeding is more often reported when treating lesions close to hilum.

Pleural effusion, usually of small volume and self-limited, can occur in case of peripheral lesion (40). Larger or long-lasting effusion should suggest a more serious condition as a hemothorax or an empyema.

Bronchopleural fistula occurs in less than 1% of procedures but may be difficult to resolve (Fig. 9). Among exceptional complications, gas cerebral embolism (51, 52) and needle-tract tumor seeding must be

*Fig. 9.* — Bronchopleural fistula. Patient with past-history of multiple sequential lung metastases from a renal cancer. He underwent serial lobectomy and multiple surgical wedge resections. A few years later, two new metastases were ablated using a Cool-tip RF device. In the recovery room, the patient presented with an episode of carbonarcosis requiring positive pressure ventilation. A bronchopleural fistula developed and was responsible for right pneumothorax and parietal emphysema that took 3 weeks to recover. Control CT image shows the fistula (arrow) between a bronchus and the cavitated treated lesion. Note a small remaining pneumothorax (arrowhead).

mentioned (53). Micro-emboli of gas, detectable by carotid US, have no neurological impact (3). A careful technique should reduce the risk of tumor dissemination during the procedure (17).

Despite a possible transient decrease during the first 3 weeks after ablation, the overall respiratory function tested at 3, 6 or 12 months after the intervention shows no degradation (25, 41, 42, 47).

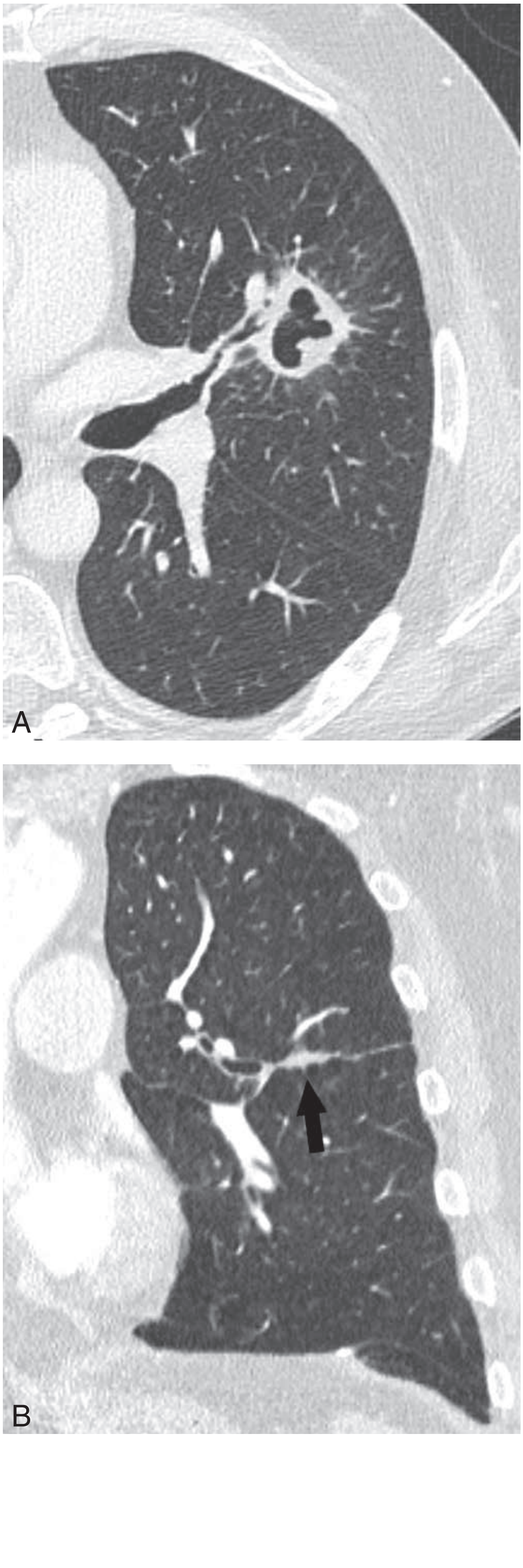



*Fig. 10.* — Cavitation and linear scar after ablation. A: Control CT image performed 1 month after ablation shows an asymptomatic cavitation after ablation of a squamous cell lung cancer of the left upper lobe. Follow-up was uneventful. B: Control coronal CT coronal reformat obtained at 10 months shows a simple linear scar (arrow). PET-CT showed no FDG uptake (not shown).

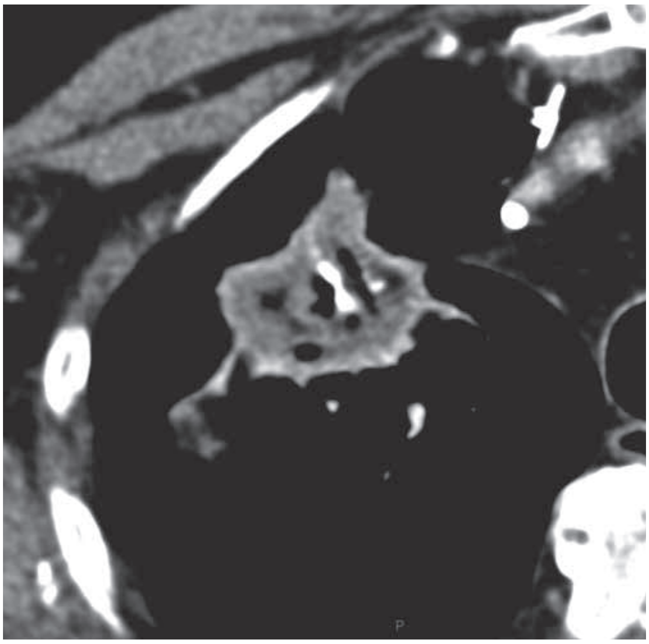


*Fig. 11.* — Inflammatory reaction around the ablation zone. Patient with past-history of metastatic colo-rectal cancer who underwent multiple wedge resections in both lungs. Recurrence was demonstrated at the site of a pulmonary resection in the right upper lobe and was treated wit Cool-tip RF ablation. Control CT image at 2 months after ablation shows absence of enhancement in the center of the thermolesion, some gas bubbles and regular enhancing peripheral rim corresponding to an inflammatory reaction. The high density structures in the center of the lesion correspond to surgical staples. Further follow-up shows cavitation of the lesion without any recurrence.

## Follow-up

Early detection of residual or recurrent tumor is crucial for proper management of the patient, possibly resulting in a new session of ablation. Follow-up imaging of ablation is difficult and must be known by all interventional and non-interventional radiologists. Mainly contrast-enhanced CT and PET-CT are used for the follow-up.

The lesion size alone is not considered as a reliable criterion of complete necrosis during the first 6-12 months. Consequently RECIST is rarely used after ablation and follow-up evaluation criteria should be adapted to the ablation technique (54). Overablation technique to obtain safety margins and inflammation secondary to thermal injury result in a thermolesion larger than the target tumor (Fig 4, 7 and 8). The maximum size is reached within 24 to 48 hours or during the first week after ablation, although growth in the next few weeks has been reported (55). Subsequently, the lesion remains stable or decreases in size, but the parameters of shrinking are not established so far (2). Any increase in size after one week and *a fortiori* 3 or 6 months after ablation should indicate tumor recurrence. While retracting, the lesion shows more angular contours, leaving eventually a linear scar (Fig. 7 and 10). The final sequella may however remain nodular, especially if the target lesion was initially larger than 2 cm, and sometimes even larger than the initial lesion (21, 56).

Enhancement after IV injection of contrast medium should also be evaluated, as an area of complete necrosis theoretically shows no contrast uptake. Enhancement greater than 10-15 HU or more than 50% of the enhancement of the target lesion before ablation should be suspicious of recurrence, especially when nodular, central, irregular or eccentric, or in contact with a vessel. Enhancement of inflammatory granulation tissue around the ablation zone can be seen as a peripheral rim during the first 6 months (Fig. 11). Bubble-like lucencies or cavitation in the lesion, usually asymptomatic and considered as a sign of good prognosis, can be visible in 30 to 50% of cases (Fig. 10 and 11). Cavitation usually disappears after 6-9 months (48, 55, 56). Finally, inflammatory hilar and mediastinal lymphadenopathies may appear during the first 3 months and then regress from 6-month (21). It is important to note that the gradual evolution of the ablation lesion to a fibrous linear scar, cavitation or atelectasis does not exclude the possibility of a subsequent local recurrence, emphasizing the importance of a continuous follow-up (56).

CT morphological analysis has limitations as an incomplete treatment may only be depicted after several months of follow-up in some cases (41, 56). MRI could better appreciate an early recurrence thanks to its superior contrast resolution (7, 14, 21). Experimental results of diffusion MRI seem particularly promising by detecting recurrences within 3 days after ablation (57).

PET-CT is more sensitive than CT alone in detecting residual tumor or recurrence in oncologic practice (24). The role of PET-CT in the early period after ablation, however, is debated in the literature. While some authors suggest its utility for the early detection of recurrence (12 to 24 hours), false positive results due to local inflammation or lymph nodes that may be found in 10-20% of cases suggest that PET-CT should better be obtained 3 to 6 months after treatment (21, 58, 59) (Fig. 4).

Various follow-up algorithms are proposed in the literature. In practice, as an example, CT is often performed at 24 hours, 1 month, and then every 3 months during the first year and every 6 months during the second year. CT will be combined with PET at 3- or 6-month, then every 6 months, or when CT is equivocal.

## Future

Percutaneous ablation is still currently considered as a standalone technique of treatment. The true position of ablation in the complex oncologic armamentarium remains to be defined. Future goals are to evaluate the long-term results of ablation compared to other techniques such as surgery and stereotactic radiotherapy, and to evaluate the association of ablation with other type of treatments, including adjuvant or neoadjuvant chemotherapy, and targeted therapies reducing tumor vascularization (60).

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