Received:
5 September 2014

Revised:
20 November 2014

Accepted:
1 December 2014

doi: 10.1259/bjr.20140598

Cite this article as:

Smith SL, Jennings PE. Lung radiofrequency and microwave ablation: a review of indications, techniques and post-procedural imaging appearances. *Br J Radiol* 2015;88:20140598.

REVIEW ARTICLE

Lung radiofrequency and microwave ablation: a review of indications, techniques and post-procedural imaging appearances

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ABSTRACT

Lung ablation can be used to treat both primary and secondary thoracic malignancies. Evidence to support its use, particularly for metastases from colonic primary tumours, is now strong, with survival data in selected cases approaching that seen after surgery. Because of this, the use of ablative techniques (particularly thermal ablation) is growing and the Royal College of Radiologists predict that the number of patients who could benefit from such treatment may reach in excess of 5000 per year in the UK. Treatment is often limited to larger regional centres, and general radiologists often have limited awareness of the current indications and the techniques involved. Furthermore, radiologists without any prior experience are frequently expected to interpret post-treatment imaging, often performed in the context of acute complications, which have occurred after discharge. This review aims to provide an overview of the current indications for pulmonary ablation, together with the techniques involved and the range of post-procedural appearances.

While thermal ablation is now an accepted technique in the management of patients with chest malignancy, it is often restricted to tertiary referral units. General radiologists may be unfamiliar with the technique, but they are frequently expected to interpret complex post-treatment imaging. Although ablation is a safe technique, with a specific mortality rate of between 0.4% and 2.6% and a major complication rate (as defined by the Society of Interventional Radiology as one requiring remedial action or where the patient experiences significant morbidity) of 9.8–17.1%, it is important for radiologists to be aware of the wide range of post-treatment appearances.^{1–3} The aim of this review is to describe these appearances and consider the current indications for ablation together with the techniques involved and the evidence to support its use.

No ethics committee approval was required for this review.

Lung thermal ablation can be used to treat both primary and secondary thoracic malignancies. Treatment criteria vary but, locally, we will consider patients with up to five pulmonary metastases <3.5 cm in diameter (uni- or bilateral) and primary tumours of ≤3 cm in diameter. These are only guidelines, and we have treated larger tumours, accepting that the probability of complete ablation is

reduced. The aim of treatment is generally to ablate all of the visible disease with the intention of achieving complete disease remission.

Before treatment, it is obviously desirable to have confirmatory histology, but this is often not possible, particularly for small lesions. In patients with a known malignancy, clinical context is usually sufficient evidence to progress to ablation of new metastases. In primary tumours or where there is clinical doubt, lung biopsy is performed prior to ablation.

Available techniques involve tissue freezing (cryoablation) or heating [radiofrequency ablation (RFA) or microwave ablation (MA)]. This review is limited to RFA and MA, which in the UK are the most commonly used methods. To date the predominant modality has been RFA. With this technique, a sinusoidal current of frequency 400–500 kHz is passed between an electrode and grounding pads, which are normally applied to the patients' legs. Ionic agitation in the tissues adjacent to the electrode tip leads to local frictional tissue heating. When in excess of 60 °C, instantaneous protein denaturation occurs. MA utilizes much higher frequency electromagnetic radiation, typically 915 MHz to 2.45 GHz. Rapid heating owing to forced rotation of polar molecules leads to higher temperatures than

can normally be achieved with RFA. Much of the available literature is based upon outcomes after RFA, but there is a growing body of evidence to support MA.^{4–7}

Microwave does have certain theoretical advantages in that ablation times are typically much shorter (2–5 min, as opposed to 12–15 min for a similar-sized treatment area). Energy propagates directly through air and tissue, and the high intrinsic impedance of lung tissue is therefore not a barrier to effective treatment. Charring, which can effectively impede the current in RFA by causing a high tissue resistance, is not an issue. There is also some suggestion that recurrence, which can occur because of the cooling effect of adjacent vessels (the so called “heat sink” effect), is reduced, although there is little rigorous data to support this. Recent guidance from the National Institute for Health and Care Excellence has summarized the case study data for MA in the chest and was unable to draw any firm conclusions on its safety or efficacy, but because its mechanism of action is very similar to RFA, similar outcomes are expected.⁸ To date microwave antennae have suffered from a rather oblate ablation zone, but manufacturers are now producing devices that deliver a more spherical zone, similar to that seen with RFA.

Evidence to support the use of thermal ablation, particularly for metastases from colonic primary tumours, is now strong, with survival data in selected groups of patients approaching that seen after surgery.^{9,10} A review of the literature to 2008 demonstrated a median reported rate of complete ablation of 90% with a high variability ranging from 38% to 97%.¹¹ There is growing evidence that size is the most important predictor of local control, and tumours <2 cm in diameter can be successfully ablated with a single treatment in 78–96% of cases.^{12–14} Because of these results, the use of ablative techniques is growing, and the Royal College of Radiologists predicts that the number of patients who could benefit from such treatment may reach in excess of 5000 per year in the UK.¹⁵ It should be noted that overall survival is a poor indicator of the efficacy of treatment, as the literature is predominantly based upon cohort studies where survival is highly influenced by patient selection. For this reason, a better marker of success is probably local disease control. It is also noteworthy that there are no randomized controlled trials comparing ablation with lung resection or stereotactic body radiotherapy (SBRT).

Primary lung tumours

The use of ablation in primary lung tumours is driven by the fact that approximately one-third of non-small-cell lung cancers (NSCLCs) are unsuitable for curative surgery. A recent retrospective analysis in a group of 64 patients showed similar outcomes when thermal ablation and sublobar resection were compared, and other studies suggest a particular advantage of local ablation in medically unfit patients.^{16,17} As yet, there are no data available comparing ablation with high-dose-targeted radiotherapy. However, in a recent review of the literature, there is clear support for SBRT in the treatment of early NSCLC. This review concluded that stereotactic ablative therapy offered a 5-year local control rate of 83.0–89.5% as opposed to 58–68% with RFA, which had a short follow up of only 18 months. Both overall survival and cancer-specific survival were also better with stereotactic ablative therapy with a 3-year overall survival

ranging from 38% to 84.7%, and a cancer-specific survival of 64–88%, whereas overall survival data were only available for two radiofrequency studies and reported as 47–74%. Furthermore, the post-procedural morbidity was higher for RFA at 33–100%, mainly owing to the incidence of pneumothorax. Radiation pneumonitis and rib fracture were the most frequently seen post-radiotherapy complications seen in 3–38% and 1.4–6.0%, respectively.¹⁸

A more recent review of RFA in NSCLC reached a similar conclusion. RFA was shown to have a higher local failure rate, with 31–42% of patients showing local progression and overall survival rate lower than SBRT. The authors of this study conclude that RFA may be best reserved for patients with early stage NSCLC who are unfit for surgery or sublobar lung resection.¹⁹

Pulmonary metastases

The International Registry of Lung Metastases reported in 1997 that patients with completely resected lung metastases had a 5-year survival of 36% as opposed to 13% for patients with no surgery. It was also noted that those patient with fewer metastases and a long disease-free interval had an improved survival.²⁰ Such observations are the main driver for the use of aggressive local ablative therapy in the context of oligometastatic disease.

The Response to Radiofrequency Ablation of Pulmonary Tumours (RAPTURE) multicentre prospective trial, which reported in 2008 and included patients with both primary and secondary tumours, showed a 99% technical success rate and a 2-year overall survival rate of 48% in patients with NSCLC and 66% in patients with pulmonary metastases from a colorectal primary.⁹ Many small observational studies suggest a survival advantage when small volume disease is treated by ablation. A study of 71 patients with 155 unresectable colorectal lung metastases showed an overall survival of 46% at 3 years. In a selected subgroup of patients with metastases <3 cm in diameter and no extrapulmonary metastases, this rose to 78%.²¹ 3-year survival data for patients with lung metastases from a colorectal primary have recently been reported as 57–77%.^{10,22} The presence of treated liver metastases, the number of pulmonary metastases ablated, previous treatment with systemic chemotherapy or prior lung resection did not appear to alter outcome.

Local control for all tumour types does seem to be influenced by the size of the treated lesions, with lesions in excess of 3 cm at the time of treatment having a much higher incidence of local progression.²³ An early report by Lee et al²⁴ described success rates of only 38% for tumours >50 mm. In a study of 198 colorectal lung metastases, the 1-, 3- and 5-year local tumour progression rates were found to be 10.1%, 20.6% and 20.6%. 1-, 3- and 5-year survival rates were 83.9%, 56.1% and 34.9% with a median survival of 38 months. In this study, a maximum tumour diameter of 3 cm, single lung disease, lack of extrapulmonary metastases and normal carcinoembryonic antigen were associated with a better prognosis.²⁵

Local ablation has been used in multiple other tumour types, including sarcoma, kidney, hepatocellular carcinoma, breast and neuroendocrine tumours.

A recent article reported a median 2-year progression-free survival of 23% in patients with low volume sarcoma metastases treated with ablation.²⁶ Prior to this in 2011, Palussiere et al²⁷ reported 1- and 3-year survival of 92.2% and 65.2%, respectively, with a median disease-free survival of 7 months.

In a small retrospective study of 39 patients with unresectable renal cell carcinoma pulmonary metastases, the authors found a possible survival advantage for those treated with RFA. Patients were divided into two groups, one where treatment was with curative intent and a second group where there was extrapulmonary disease or other adverse features. The overall survival rates in the curative and palliative groups were 100% and 90% at 1 year, 100% and 52% at 3 years and 100% and 52% at 5 years, respectively.²⁸

Hiraki et al¹⁴ reported results on the outcome of patients with lung metastases from hepatocellular carcinoma. In 32 patients where RFA was preformed with curative intent, the overall survival was 87% at 1 year and 57% at 2 and 3 years with a median follow up of 20.5 months. Better outcome was seen in those with no liver recurrence, Child–Pugh A status, no liver cirrhosis and an alpha-fetoprotein level of $<10 \text{ ng ml}^{-1}$ at the time of RFA. The authors suggest a role for RFA in the context of truly oligometastatic hepatocellular carcinoma in an otherwise fit patient.²⁹

The role of ablation in tumour cytoreduction is controversial. Early reports of debulking hepatic metastases from breast carcinoma suggest that the technique is feasible, but it is difficult to draw any firm conclusions with regard to survival advantages.³⁰ There are case reports of symptom relief after debulking of thoracic malignancy, but this remains an area where further investigation is required.³¹ There may be a role for the debulking of small renal cell carcinomas in the context of metastases.³² Similarly, ablation has been combined with external beam radiotherapy, systemic chemotherapy and chemoembolization, but further discussion is outside the scope of this review.

ABLATION TECHNIQUE

Many centres prefer to use general anaesthesia (GA), but in our experience, treatment is generally very well tolerated with conscious sedation. No difference in outcome was reported by Hoffmann et al³³ when comparing procedures performed under GA or sedation; however, several of the treatments could not be completed under sedation and a second GA was needed. A review of the liver RFA literature describes GA as an independent factor associated with complete tumour ablation.³⁴ We prefer GA for lung basal and diaphragmatic lesions, which can be very mobile and difficult to target without suspended respiration. GA is also preferred when a long ablation time is likely, when multiple lesions are treated in the same session or multiple treatments of a single large lesion are necessary. However, in our experience, the majority of pulmonary ablations, even those abutting the pleura, can be performed safely under adequate conscious sedation. We have found the use of bispectral index monitoring a very useful adjunct to clinical assessment during sedation. This simple index gives an indication of the level of consciousness and can be very helpful, particularly in those patients who react unpredictably to sedation.

The patient is positioned on the CT couch to allow a safe access route. CT fluoroscopy with single shot axial image acquisition is used routinely. Full CT helical imaging is used to confirm the position of the electrode with regards to both the lesion and any adjacent structures. Reviewing this data in multiplanar format is very useful. Needle positioning is planned such that the predicted ablation zone encompasses the mass with an adequate margin (see below). It is not necessary to pass the electrode directly through small lesions and a final position with the tip immediately adjacent to the metastasis is usually adequate, provided the predicted ablation zone yields an adequate margin of safety. Larger lesions should be punctured as near to their centre as possible.

There are a number of RFA devices that can be broadly divided into two groups. Most popular are single-needle electrodes that tend to be water cooled to prevent tissue charring adjacent to the tip, and these can be used in isolation or as a multiple group of electrodes when a larger treatment area is required. Other manufacturers offer expandable electrodes with fine metallic tines that are deployed through a coaxial access needle. In our experience, this latter device offers some advantages in the lung, as once a lesion is engaged by the tines, it is less likely to displace, particularly in the context of an enlarging pneumothorax. There is some suggestion that electrode design may have an influence on the success of the treatment. Hiraki et al¹⁴ found reduced success with straight water-cooled electrodes, as opposed to those with expanding tines.

We prefer to use the multiple tine-based system centrally in lung parenchyma and the single electrode system when tine deployment could damage adjacent structures.

Microwave antennae tend to be of larger gauge (13 vs 14 gauge). Because of the design of the microwave feed point at the tip of the needle, antennae also tend to be less robust and fracturing of the needle tip is described.³⁵ For this reason, care should be taken to avoid any needle leverage during placement. This is in contrast to RFA electrodes, which can be used to manipulate pulmonary lesions away from adjacent structures (Figure 1).

It may be necessary to induce a pneumothorax or instil a fluid buffer using 5% dextrose to prevent thermal damage to adjacent structures. This is best performed after electrode placement, as pneumothoraces can behave unpredictably making subsequent targeting difficult.

Some devices provide an end of treatment temperature, while other algorithms are based upon changes in tissue impedance. It is sometimes useful to insert a separate temperature probe at the margins of the ablation zone, particularly if there is concern over causing thermal damage to adjacent structures. This provides real-time monitoring, giving the operator the ability to titrate the treatment to the temperature at the edge of the ablation zone. Depending on the size of the lesion, it may be necessary to perform overlapping ablations to achieve an adequate treatment.

Post-ablation follow-up regimes vary, but we perform an immediate post-ablation chest CT, mainly to check for

Figure 1. A 32-year-old male patient with metastatic sarcoma. Normal post-ablation appearances: (a) immediate post-treatment CT after ablation of a small subpleural metastasis from a soft-tissue sarcoma. There was a small iatrogenic pneumothorax introduced to protect the chest wall from thermal damage (black arrow). Note the satisfactory zone of ground glass change, which completely encompasses the metastasis (white arrow). (b) CT performed at 1 month after treatment shows normal maturation of the ablation zone with thickening of the outer zone of fibrosis (arrow). Note that the small localized pneumothorax persists. The patient was asymptomatic.

complications and to assess the adequacy of the ablation zone (see below). A new baseline post-contrast CT is performed at 1 month,⁹ with the next routine follow-up at 4 months post treatment when a whole-body contrast-enhanced CT is performed. Local recurrence can occur early or late, meaning protracted imaging follow up is required.³⁶ There is no clearly defined follow-up protocol, but at our centre, for colorectal metastases, we image at 3–4 monthly intervals for the first 2 years after treatment and 6 monthly thereafter to 5 years. To reflect differences in tumour biology, slightly less aggressive follow up is generally used in renal and sarcoma metastases, but we vary the regime according to the patient's history.

NORMAL POST-TREATMENT APPEARANCES

Immediate post treatment CT shows a halo of ground glass opacification (GGO) surrounding the lesion. Although this can be short lived, it is a useful sign as if it encompasses the lesion with a satisfactory margin, there is good correlation with cell death and thus successful treatment.^{12,37} Over a period of a week, the GGO usually changes to more dense airspace opacification.³⁸ GGO represents a transition from non-viable to viable tissue, and the outer margin of the shadowing probably overestimates the zone of complete ablation by 3–4 mm, emphasizing the need for an adequate treatment margin, analogous to the surgical margin in a resected tumour^{39,40} (Figure 2). It is well known that tumours may extend microscopically into the

adjacent lung parenchyma by 6–8 mm, and it is therefore suggested that the ablation zone should be at least 1 cm larger than the lesion.^{37,40,41} In an article by de Baère et al,¹² the ratio of post-treatment GGO to the pre-treatment tumour area was found to be predictive of success. If the ratio was at least four, the rate of complete ablation at 4 months was found to be 96%. For a ratio of three or less, the success rate was 61%.

Animal studies have shown the changes that occur in the ablated lung. In a rabbit model, the GGO correlated with lung thermal injury. Progressive necrosis was recorded within the treated area consistent with heat-induced cell death.⁴² In a pig model, GGO was found to represent a combination of lung cell death and local haemorrhage, and the apparent increase in the size of the treated lesion was owing to the appearance of granulation tissue.³⁹

Between 1 and 3 months, the margin of the ablation zone becomes better defined and denser, consistent with organizing fibrosis. Centrally, there can be a variety of appearances. Cavitation is common, occurring with an incidence of 14% at 1.5 months in a series of 100 lung ablations, being more common in patients with lesions near to a large airway or chest wall and in those with pre-existing emphysema. It may also be more common in primary lung tumours, as opposed to metastases.⁴³ The cavity often has a bizarre central appearance.⁴⁴ Cavities can

Figure 2. To show the range of normal post-ablation appearances: (a) CT at 3 months after ablation of two colorectal cancer metastases. Note variation in appearance. (b) Same patient as (a) at 1-year post ablation showing maturation of ablation zones.

contain gas, fluid or dense ground glass shadowing, and there is considerable overlap with the appearances of lung abscesses. At 3 months, the ablated lesion is usually slightly larger than baseline owing to residual oedema, but by 6 months, the ablation zone is usually starting to decrease in size (Figure 3). Any increase in volume at this stage is very suspicious of recurrence.⁴⁵ Enhancement with iodinated contrast agents is variable. In our experience, arterial enhancement is common early after ablation, reflecting reactive hyperaemia in the tissues at the margin of the treatment zone. We have found that enhancement above baseline density is unusual after 6 months, and if present should again raise the suspicion of revascularization and thus local recurrence. Between 3 months and a year, the ablation zone usually shows retraction. The end appearances are variable and can range from a rounded area of relatively dense scarring to a barely perceptible region of atelectasis or fibrosis. In our experience, the track of the ablation electrode is often clearly visible, sometimes persisting in excess of 6 months. Pleural effusions are common as are small pneumothoraces. These have usually resolved by 3–6 months.

Generally, lung ablation has no measurable long-term effect on pulmonary function. No changes in formal pulmonary function tests were found 1 month after RFA in a study by de Baère et al.¹² There is no defined cut-off with respect to forced expiratory volume (FEV) below which ablation is considered unsafe. Treatments are reported in patients with an FEV of $<0.8 \text{ l s}^{-1}$, and locally, we have treated a patient with severe emphysema with an FEV of 0.5 l s^{-1} , but it is important that the patient is counselled concerning the increased risks. Patients with a single lung have also been treated. In a retrospective analysis published in 2007, 4 deaths occurred in 153 patients as a consequence of RFA and 2 of these 4 were patients with single lung.²

UNEXPECTED FINDINGS

Pneumothorax

The rate of traumatic pneumothorax developing during a procedure can be as high as 50% with these authors reporting the need for a chest drain in 50% of these.⁴⁵ The threshold for placing

a chest drain varies, but our experience is of a lower incidence of chest drain insertion, closer to 5–10%. The incidence of pneumothorax requiring a chest drain seems to be related to the number of lesions treated and the length of the procedure.⁴⁶ Pre-existing emphysema is also an independent risk factor for pneumothorax requiring pleurodesis.¹ There may also be an increased risk in the context of previous thoracic surgery.⁴⁷ We often deliberately introduce air into the pleural space during the procedure to act as a thermal buffer to prevent chest wall damage or injury to adjacent structures. Any excess pleural air is usually aspirated at the end of the procedure. Persistent air leak as a consequence of broncho-pleural fistula is reported but is very rare. It should be suspected where a pneumothorax fails to resolve with a simple chest drain.⁴⁸ Surgical emphysema is common but is usually self-limiting. Virtually, all pneumothoraces requiring treatment are present on the immediate post-treatment CT, and in our experience, delayed pneumothorax is very rare. However, a retrospective analysis of 194 sessions of thoracic RFA found an incidence of delayed pneumothorax of 24% with a mean duration of 24 h after treatment. A higher incidence of delayed pneumothorax was seen in patients, where the post-treatment GGO reached the pleura.⁴⁹

Pleural fluid

The incidence of an aseptic pleuritis is reported as 2.3%.¹ The number of pleural punctures and previous systemic chemotherapy are significant risk factors.¹ Large pleural effusions are relatively uncommon and can simply be reactive. If completely asymptomatic, it is our practice to manage them conservatively. If patients are symptomatic or have abnormal inflammatory markers, aspiration is advised (Figure 4). Haemothorax is also rare but should obviously be suspected in the context of rapid accumulation of fluid and cardiovascular compromise. In our experience, some pleural hyperenhancement can also be seen on early follow-up CT, probably reflecting a degree of pleural hyperaemia.

Pulmonary abscess

Pneumonia occurs in 1.8% of treated patients with an increased risk in patients who have received prior radiotherapy. Age also

Figure 3. Pleural change. Changes must be interpreted in the correct clinical context: (a) a 72-year-old patient with metastatic colorectal cancer. CT at 3 months post ablation subcentimetre right lung lesion. Moderate persistent pleural effusion. This was asymptomatic and needed no intervention. It had resolved by 6 months. (b) 74-year-old patient with metastatic colorectal cancer. CT at 1 month after ablation of a 1-cm lower lobe metastasis from a colorectal primary. The patient was readmitted acutely unwell with a high fever and constitutional symptoms. The pleural effusion was drained and the lung collection aspirated. The contents were infected. The patient was treated with intravenous antibiotics and improved over the next 7 days.

Figure 4. A 69-year-old patient with metastatic colorectal cancer. Immediate post-treatment CT. There is a moderate degree of parenchymal haemorrhage surrounding a 15-mm metastasis (arrow). Some haemorrhage is a near universal finding and is usually asymptomatic and resolves spontaneously.

seems to be an independent risk factor for pneumonia.¹ Lung abscess is rare, with a reported incidence of 1.6% patients.¹ It is more common in the context of pre-existing inflammatory lung disease. Pre- or post-procedure antibiotics are not recommended routinely, but some centres do advocate their use in high-risk patients. Clinical signs of sepsis coupled with a thick-walled cavitating mass on CT should raise the possibility of an abscess. There is often considerable abnormality in the adjacent lung with an associated pleural effusion (Figure 4). As described above, the uncomplicated ablation zone can have a very “abscess-like” appearance up to 3 months after treatment and intervention should be avoided unless there is good clinical evidence of infection.

Vascular complications

Pulmonary haemorrhage

Mild pulmonary parenchymal haemorrhage is a universal finding on the immediate CT. This usually settles, and significant haemoptysis is uncommon. Large parenchymal haemorrhage occurs in 7–8%^{45,50} but is often asymptomatic (Figure 5).

Tumour size and platelet count have been identified as independent risk factors for haemorrhage.¹ Using the Common Terminology Criteria for Adverse Events system, grade 4 haemorrhage (defined as life threatening) is rare and reported at 0.3% in a large series of ablations.¹ Such massive haemorrhage is usually as a result of bleeding from a bronchial artery operating at higher pressure than the pulmonary circulation.

Patients occasionally report a cough productive of “dirty” or blood-stained sputum in the weeks after ablation, but this is usually self-limiting.

There are several case reports of non-fatal large air embolism occurring as a consequence of electrode placement, rather than the ablation itself.^{51,52}

Pseudoaneurysm

Vascular injury resulting in pseudoaneurysm is uncommon, occurring in 0.2% of patients in a series of 538 pulmonary ablations. The risk is higher when the treated lesion lies close to a large vessel. Most pseudoaneurysms are small and are often asymptomatic (Figure 6a,b). Spontaneous resolution is reported, but rupture and massive haemorrhage can occur.⁵³ Rupture has been reported between 3 and 17 days post treatment.⁵³ Urgent catheter angiography and embolization can be life saving (Figure 7a,b).

Lung inflammation

Acute interstitial pneumonitis has been reported although its aetiology is uncertain. In a retrospective study of 327 ablations in 130 patients, the incidence of interstitial pneumonitis was 0.6%. The risk was greater in patients with tumours of ≥ 2 cm in diameter and in those individuals who had previously received external beam radiotherapy. The typical CT findings are of dense ground glass change, interstitial thickening and frank consolidation. The disease can be fulminant and has a 50% reported mortality.⁵⁴

Thoracic wall injury

With lesions near to the pleura, there is a risk of pleural and chest wall injury.⁴⁷ A variety of manoeuvres, including the introduction of a pneumothorax or injection of fluid (usually local anaesthetic and/or 5% dextrose) can be used to prevent this (Figures 1a and

Figure 5. A 74-year-old patient with metastatic colorectal cancer. Follow-up CT after treatment of a subcentimetre metastasis from a colorectal primary. (a) CT at 3 months after treatment shows a 5-mm avidly enhancing area consistent with a false aneurysm (arrow). This was asymptomatic, and a decision was made to treat this conservatively. (b) Follow-up CT 3 months after (b) shows spontaneous resolution of the aneurysm.

Figure 6. A 60-year-old patient with metastatic soft-tissue sarcoma. Unwell 24 h after ablation with chest pain and haemoptysis. (a) Digital subtracted angiogram performed 3 days after lung ablation showing aneurysm arising from a segmental pulmonary artery. This was successfully coiled. (b) CT at 1 year shows the coils. The aneurysm cavity is obliterated and shows no flow. Patient was asymptomatic.

2b), but occasionally with lesions in difficult locations, some thermal damage to adjacent tissues is unavoidable. Particular care is needed when treatment is performed close to major nerves (Figure 1). Damage to intercostal nerves can lead to persistent neuralgia, and these symptoms can be difficult to manage. However, the pain is almost always self-limiting. Superficial skin burns can occur but should be avoided with careful multiplanar pre-treatment measurement of the electrode tip distance from the chest wall. The incidence of rib fractures related to thoracic ablation is reported to be as high as 13.5%, although the exact mechanism is uncertain.⁵⁵ These data were based upon patients receiving combined radiotherapy and ablation and are therefore likely not to be transferable to ablation alone.

Damage to the diaphragm is also reported, with an incidence of 0.1%.¹ This is usually self-limiting but frank perforation requiring surgical repair is described.⁵⁶

Tumour recurrence

Local recurrence is the commonest pattern of relapse after treatment. Tumour type is a strong predictor of recurrence with higher control rates seen in metastases from colorectal cancer than those of primary lung cancer, renal cell carcinoma and hepatocellular carcinoma and has been reported to be as high as 28% at 2 years, in a series of primary lung tumours.^{57,58} In a large review, local recurrence was reported in 12.2% of patients with a mean period to relapse of 13 months (range, 3–45 months).³⁶ In a retrospective study of 82 lung tumours, an incidence of local progression of 22% was reported with a mean local progression-free duration of 8.7 months.⁵⁹ Risk factors include size of tumour and stage of disease at presentation. Masses close to blood vessels >3 mm in diameter have a higher rate of relapse owing to undertreatment because of the so called “heat sink” effect, where tissue is cooled by flowing blood.¹³ MA, by virtue of its direct heating and more predictable heat profile,

Figure 7. Nerve damage. (a) A 78-year-old patient with metastatic colorectal cancer. Apical subcentimetre metastasis. Axial image shows treatment electrode in position (thin arrow). A second 23 G needle was introduced to inject 5% dextrose and local anaesthetic to act as a thermal buffer (fat arrow). The patient did experience transient T1 root symptoms owing to thermal damage of the lower brachial plexus. (b) A 71-year-old patient. CT image during treatment of multiple right-sided metastases from a sarcoma. The most medial lesion was in contact with the superior vena cava. There was a risk of phrenic nerve injury. To avoid this, a pneumothorax was introduced after the lesion had been targeted with the radiofrequency electrode. Gentle traction was then applied to open the pleural space and create an air gap between lesion and vena cava as a thermal buffer. Asterisk indicates the superior vena cava, white arrow indicates radiofrequency electrode in the upper lobe metastasis and the black arrow indicates a 21 G needle in the plural space.

Figure 8. Tumour recurrence in a 79-year-old patient with metastatic colorectal cancer. (a) CT image at 3 months after treatment of a subpleural metastasis with a satisfactory appearance. (b) CT at 6 months shows a change in the contour of the ablation zone diagnostic of local recurrence (arrow). This was successfully reablated.

may offer an advantage over RFA for lesions close to vessels, but as yet, there is no good evidence to support this.

In a further review of 138 lung tumours, an incidence of recurrence of 32% was reported with the most significant risk factor again being tumours >2 cm at the time of treatment.⁶⁰

Signs of relapse can be very subtle, particularly on early follow-up CT. Any change in lesion contour, increase in volume or contrast enhancement after 6 months is highly suspicious (Figures 8 and 9); however, there are no well-defined criteria to assess post-ablation appearances on CT. A recent study has described the following features as being most useful: a change in dynamic enhancement (increasing contrast material uptake in the ablation zone, nodular enhancement measuring >10 mm, any central enhancement >15 HU and enhancement greater than baseline at any time after ablation) and growth of the treatment zone after 3 months, peripheral nodular growth and change from GGO to solid opacity.⁶¹

Modalities other than CT have been used to follow up ablated tumours. Several studies exploring the role of positron emission tomography (PET) have been published, and these suggest a characteristic set of findings in the successfully ablated tumour, including a large decrease in the standardized uptake value

(SUV) in the ablated area. PET-CT may detect recurrence earlier than does conventional CT, but there is limited evidence to support this.^{62–65} In a study of 68 patients, an SUV of <8 was found to be a predictor of improved disease-free survival. After treatment, reduced recurrence-free survival correlated with an unfavourable fluorine-18 fludeoxyglucose uptake pattern, the absolute value of the post-RFA SUV and an increase in SUV over time after ablation.⁶⁶ We do not use PET-CT routinely for follow up.

The use of diffusion-weighted MR and MR and CT perfusion have also been reported, although again, their effectiveness is undefined.^{67,68}

Needle tract seeding is rare. In a review of 661 procedures, an incidence of 0.2% has been reported.⁶⁹ Care should be taken when manipulating the needle not to withdraw the electrode through tumour before adequate treatment. Similarly, if a second needle is used to deliver local anaesthetic or induce a pneumothorax, special attention is needed to ensure that it does not pass through tumour tissue.

CONCLUSION

Pulmonary RFA is now an accepted treatment for lung metastases and some lung primary tumours. There is growing

Figure 9. Recurrence near a vessel in a 74-year-old patient with metastatic colorectal cancer. (a) CT image during ablation of a subcentimetre metastasis very close to the lower lobe pulmonary artery. Arrow shows radiofrequency electrode in a small metastasis abutting a lower lobe artery. (b) CT at 3 months shows clear nodular tumour regrowth (arrow). Lesion was undertreated owing to “heat sink” effect from the adjacent vessel.

evidence of its efficacy, particularly in those patients with oligometastatic disease and survival in patients with metastatic colorectal cancer treated with RFA seems better than when patients are treated with chemotherapy alone. The key to successful treatment depends upon patient selection. Those patients with true oligometastatic disease and a long disease-free interval between the treatment of the primary tumour and the development of metastases have better outcomes. Lesions <3 cm in diameter, situated away from large vessels are ideally suited for ablative therapy and have a low risk of local recurrence.

The literature suffers from an absence of randomized control trials, and there are many unresolved issues, including the role of ablation in a variety of other tumour types, the efficacy of ablation when combined with other treatments and its potential for tumour debulking, particularly as a prelude to systemic therapy. However, the use of this technique is likely to grow and non-specialist radiologists are increasingly likely to encounter patients who have undergone pulmonary ablation. Post-ablation imaging findings are complex, and it is vital that thoracic complications are distinguished from the range of normal appearances.

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