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REVIEW

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Minimally invasive surgical techniques in patients with intractable epilepsy with CT-guided stereotactic cryoablation as a superior alternative: a systematic review

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Abstract

Background: Stereotactic cryoablation is a minimally invasive surgical technique that has been used to treat disorders of the brain in the past; however, in current practice, it is primarily used for the treatment of liver, kidney, lung, prostate, and breast neoplasms. In this paper, currently used surgical methods to treat medically refractory seizure disorder are reviewed, and a case is made for the use of stereotactic cryoablation.

Main body: Anterior temporal lobectomy is the gold standard for temporal. There are also several variations of this procedure. Since this is a resective surgery, it can result in neurological defects. To obviate this problem, minimally invasive surgical techniques such as radio frequency ablation and laser interstitial thermal therapy are currently being used for intracranial targets. Cryoablation offers certain advantages over thermal ablations. Cryoablation studies in brain, renal, breast, and other neoplasms have shown that cryoablation has superior abilities to monitor the ablation zone in real time via computerized tomography imaging and also has the capability to create lesions of both smaller and larger sizes. This allows for safer and more effective tumor destruction.

Short conclusion: Based on the review, the authors conclude that further investigation of the use of stereotactic cryoablation in patients with medically intractable epilepsy is needed.

Keywords: Seizure disorder, Seizure surgery, Stereotactic surgery, Cryoablation

Background

Epilepsy is one of the most prevalent, chronic neurologic diseases worldwide, affecting approximately 50 million people. 3% of the general population will be affected by epilepsy [1]. Although this disease can be debilitating, approximately two of three patients become seizure-free with anti-epileptic drugs (AED) alone. However, approximately 19% of patients will have medically refractory epilepsy all their life [2].

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Several studies have shown that up to 25% of patients treated with successive drug regimens will never attain seizure freedom. Furthermore, the chance of seizure freedom declines with each successive drug regimens, especially among patients with localization-related epilepsy [3]. Drug-resistant epilepsy is defined as the failure of adequate trials of two tolerated, appropriately chosen and used anti-epileptic drug schedules (whether as monotherapies or in combination) to achieve sustained seizure freedom [4].

Partial epilepsy is even more difficult to manage than generalized epilepsy. The mesial temporal lobe is the most common origin of partial epilepsy, and hippocampal sclerosis is the most common lesion that is resected in patients with mesial temporal lobe epilepsy (MTLE). Among 2200 adult outpatients with epilepsy, seizure control was obtained in only 35% of patients with symptomatic partial epilepsy and 11% of patients with hippocampal sclerosis as compared with 82% of patients with idiopathic generalized epilepsy. Temporal lobe epilepsy was the most refractory partial epilepsy to pharmacotherapy with only 20% of those patients becoming seizure-free as compared with 36% of extra-temporal lobe epilepsy patients. Structural brain abnormalities, such as hippocampal sclerosis, are a major prognostic factor in patients with epilepsy [5].

The goal of this review is to review currently available surgical methods to treat medically intractable epilepsy and to propose the benefits of using CT-guided stereotactic cryoablation as an alternative treatment modality.

Main text

Open brain resection

Anterior temporal lobectomy

In the modern era, there are variations of open and minimally invasive surgical procedures, to treat intractable epilepsy. However, anterior temporal lobectomy (ATL) continues to remain as the gold standard treatment for drug-resistant epilepsy. ATL has been studied and evaluated for decades in the treatment of epilepsy and has proven to be both an effective and durable treatment. In a study by Sperling et al., 89 patients with medically refractory epilepsy underwent ATL, resulting in a 5-year seizure freedom rate of 70%. They concluded that temporal lobectomy provides sustained seizure relief over 5 years to most patients who have surgery [6]. In a randomized control trial by Wiebe et al., 80 patients with temporal lobe epilepsy were randomly assigned to either surgery or AED treatment groups. Patients who underwent ATL were observed to have a 1-year seizure freedom rate of 58% ($p<0.001$), as compared to 8% in the medical group ($p<0.001$). They concluded that in temporal lobe epilepsy, surgery is superior to prolonged medical therapy alone [7].

Among 38 patients with medically refractory MTLE in a study by Engel et al., 15 patients underwent ATL with subsequent AED treatment and 23 patients underwent AED treatment alone. None of the 23 patients in the AED treatment group were seizure-free at the 2-year follow-up, while 73% of the patients in the surgery group were seizure-free at the 2-year follow-up with a significant improvement in quality of life. They concluded that in patients with intractable and disabling MTLE, anteromesial temporal resection plus AEDs resulted in a lower probability of seizures at the 2-year follow-up than AED treatment alone [8]. ATL has clearly been studied thoroughly and has been proven to be a superior treatment modality in patients with medically intractable epilepsy given that it yields seizure freedom rates from 60 to 80%.

Selective amygdalohippocampectomy

While ATL remains the gold standard of open resection, there still remains a wide array of other resection techniques. Selective amygdalohippocampectomy (SAH) arose as the best, viable alternative to ATL. In a study by Weiser et al., 27 patients underwent SAH achieving a seizure freedom rate of 81% with a mean follow-up of 21 months. Post-op neuropsychological follow-up showed better results when compared to patients who underwent ATL. Furthermore, learning and memory complications were less pronounced when compared to patients who underwent ATL [9].

A meta-analysis by Hu et al. reviewed three prospective and ten retrospective studies, involving 745 and 766 patients who underwent SAH and ATL, respectively. Their review revealed that there was a statistically significant reduction in the odds of seizure freedom for patients who underwent SAH compared with those who underwent ATL (OR 0.65 [95% CI 0.51–0.82], $p=0.0005$). They concluded that SAH statistically reduced the odds of being seizure-free compared with ATL, but the clinical significance of this reduction cannot be determined at this time [10]. In light of this study, it was clear that SAH was not as effective as ATL in treating patients with medically refractory epilepsy. However, SAH still remained a viable alternative.

Other techniques

In a study by Williamson et al., 10 patients with parietal lobe epilepsy underwent open resection, 9 of which had intracranial EEG monitoring. All 10 patients who underwent resection were reported to be seizure-free for 3 or more years [11]. In a study by Awad et al., 47 patients with medically intractable epilepsy due to frontal, temporal, and parieto-occipital lobe lesions underwent complete or incomplete lesion resection depending on the accessibility of the lesion. Seizure control was achieved in 94% of patients who were able to be treated with complete lesion resection. Seizure control was achieved in 83% of patients with incomplete lesion resection but complete seizure focus excision and 52% of patients with incomplete lesion resection and incomplete seizure focus excision. An important conclusion that was drawn from this study was that the extent of lesion resection was strongly associated with the surgical outcome ($p<0.003$). This is crucial because while complete lesion resection is ideal in terms of seizure resolution, an increase in the extent of resection results in an increase in the risk of complications [12].

Complications of open brain resection

Although open brain resection proved to be a groundbreaking and effective treatment for medically refractory epilepsy, its major drawbacks lay within its various medical and neurological complications. A systematic review by Hader et al. included 76 articles in order to determine the major and minor complications of focal epilepsy surgery [13]. Minor medical complications including CSF leak, intracranial/extracranial infections, aseptic meningitis, pneumonia, and intracranial hematomas occurred in 5.1% of patients. Major medical complications including hydrocephalus and intracerebral or epidural abscesses occurred in 1.5% of patients. Minor neurologic complications including cranial nerve deficits, dysphasia, memory disturbances, hemiparesis, and psychiatric complications that resolved completely within 3 months occurred in 10.9% of patients. And lastly, major neurologic complications, which include any minor neurological complication that did not resolve within 3 months, occurred in 4.7% of patients. However, they concluded that although a variety of medical and neurologic complications may occur after epilepsy surgery, permanent serious complications are not common.

In a study by Ahmedov et al., 53 patients with temporal lobe epilepsy underwent ATL. The overall complication rate was 19%; however, the rate of persistent or permanent complications was 0%. They concluded that ATL is a safe and effective surgical modality for the treatment of temporal lobe epilepsy. However, unexpected complications may be possible in this modern era and a surgeon should trust in him/herself not in modern equipment [14]. Usually, complications are due to the nature and technical difficulties involved in performing open brain resection. Depending on the extent of resection, there is always a risk of damage to healthy brain tissues. Furthermore, this risk is increased if the lesion is deeply located, as it becomes difficult for the surgeon to navigate toward the desired area [15].

Ischemic events within the territory of the anterior choroidal artery can cause significant morbidity after temporal lobe epilepsy surgery. In a study in which 422 patients with drug-resistant temporal lobe epilepsy underwent temporal lobe resection, 3.3% of patients suffered from ischemic events. Furthermore, 57% of ischemic events were due specifically to anterior choroidal artery infarction. Infarction volume showed a negative correlation trend with health-related quality-of-life score [16]. Although open brain resection, namely ATL, remains the gold standard for the \treatment of medically refractory epilepsy in the modern era, it is the myriad of complications and difficulties involved with performing open brain resection that has prompted surgeons to seek out more minimally invasive treatments.

Stereotactic radio frequency ablation

Mechanism of radio frequency ablation

Radio frequency (RF) ablation consists of creating a lesion using heat through an intracranially placed electrode coupled to an RF generator. This electrode is electrically insulated except at the tip, where the active electrode is located. The frictional heating within the tissue due to the RF ionic oscillation is the basic mechanism by which the tissue is heated and by which the RF heat lesion is created. The greatest heating occurs in the region of the highest current density, which is localized at the tip of the electrode [17].

Clinical outcomes

RF ablation was first performed by Narabayashi et al., during a study in which 60 patients with epilepsy underwent stereotactic amygdalotomy. 85% of patients were observed to have a reduction in emotional excitability and normalization of the patient's social behaviors [18]. In a study by Patil et al., nine patients with intractable seizures underwent CT-guided stereotactic volumetric radiofrequency lesioning (SVRFL), seven of which lesions were made in the amygdalohippocampal complex, two of which were made in the corpus callosum, and six of which underwent multiple subpial transection (MST). 56% of patients achieved seizure freedom with a median follow-up of 19 months, while 33% of patients achieved greater than 90% reduction in seizure activity. They concluded that SVRFL of the AHC and CC is safe and effective in controlling seizures [19]. In another study by Patil et al., 24 patients with intractable seizures underwent MST, topectomy, or stereotactic AHT. 66% of patients achieved seizure freedom with a median follow-up of 18 months, while 29% of patients achieved greater than 90% reduction in seizure activity. Satisfactory seizure control was achieved in all patients at 1-year follow-up. He concluded that minimally invasive procedures are effective in controlling intractable seizures and are safe to perform [20].

In a study by Blume et al., 14 patients with MTLE underwent magnetic resonance imaging (MRI)-guided stereotactic RF ablation. A reduction in temporal lobe complex partial seizures was observed in 13 of 14 patients [21]. In a study by Liscak et al., 51 patients with MTLE underwent stereotactic RF ablation of the amygdala hippocampus complex. At a 2-year follow-up, 78% of patients achieved an Engel I outcome, 16% of patients achieved an Engel II outcome, and 6% of patients achieved an Engel IV outcome. They concluded that stereotactic amygdalohippocampectomy is a minimally invasive procedure with clinical outcomes that are comparable to open surgery with low morbidity, thus making it a safer alternative for patients with MTLE

[22]. It is accepted that the success rate of RF ablation in treating renal cell carcinoma depends on the tumor's size and location. In the brain, neoplasms can often be deeply located and surrounded by delicate and complex structures. This creates a conundrum in which surgeons require a much safer and more accurate modality of technique to ensure optimal patient outcomes.

MRI-guided stereotactic laser interstitial thermotherapy

Mechanism of LITT

In stereotactic laser interstitial thermotherapy (LITT), laser light is transmitted from the generator to the patient's tissue through the use of optical fibers. Laser light is introduced into the patient through a diffusing tip that radiates light in a cylindrical to ellipsoid distribution along the axis of the tip. Some tips allow surgeons to conform to the complex shape of certain tumors with asymmetrical light distribution [23]. LITT can also be paired with MRI thermometry, which allows for real-time image feedback of laser thermal energy delivery, making it possible to predict the thermal damage of a planned target in the brain. Sugiyama et al. were the first to evaluate LITT in five patients with brain tumors using CT guidance. The results showed 100% tumor reduction, with no evidence of recurrence in three of five patients at 31 months. They concluded that LITT using Nd-TAG laser is easy, safe to use, and effective in the treatment of deep-seated brain tumors [24].

Clinical outcomes

In a study by Willie et al., 13 patients with MTLE underwent MRI-guided stereotactic laser amygdalohippocampotomy (SLAH). At a 2-year follow-up, 54% of patients achieved an Engel I outcome, 23% of patients achieved an Engel III outcome, while 23% of patients achieved an Engel IV outcome. They concluded that MRI-guided SLAH is a technically feasible alternative to open resection that minimizes collateral injury while demonstrating efficacy that approaches open resection [25]. In a study by Kang et al., 20 patients with MTLE underwent MRI-guided SLAH, and 53% of patients were found to be seizure-free at 6 months. The 1-year seizure freedom rate was reported at 36%. They concluded that MRI-guided SLAH is a safe alternative to ATL in patients with MTLE for reducing seizure frequency [26].

The first multicenter study of LITT for patients with MTLE by Wu et al. included 234 patients across 11 different centers. 58% of patients achieved Engel I outcomes at 1- and 2-year follow-ups, demonstrating the durability of this therapy. The complication rate was 15%, being comparable to open brain resection. They concluded that the ability to accurately target the amygdala, hippocampal head, parahippocampal gyrus, and rhinal cortices maximizes the chances of seizure freedom [27]. A systematic review was performed by Grewal et al., focusing on the seizure freedom rates of MRI-guided SLAH compared to stereotactic radiosurgery (SRS). Between nine MRI-guided SLAH studies and 10 SRS studies, seizure freedom rates were shown to be 50% in patients who underwent MRIgLITT and 42% in patients who underwent SRS. Complication rates were 20% in MRI-guided SLAG patients and 32% in SRS patients [28]. The current data indicate that, with MRI-guided SLAH, seizure freedom is achieved in 50–60% of patients with MTLE, which approaches, but does not match the rate of open ATL.

Advantages of LITT

Because it is minimally invasive, LITT has a lower rate of complication compared to open surgery. A systematic review and meta-analysis by Barnett et al. compared major complication rates between MRI-guided SLAH and craniotomy. Among eight LITT studies and 19 craniotomy studies, the neurocognitive/functional complication rates (> 3 months duration) were shown to be 5.7% for LITT patients and 13.9% for craniotomy patients. The results showed a 10% absolute risk reduction favoring LITT [29]. Furthermore, intraoperative visualization of the lesion on imaging studies allows for modifications and fine-tuning [30]. MRI-guided SLAH also offers tighter thermal control than other minimally invasive techniques and allows the surgeon to better protect critical structures from damage [31].

Disadvantages of LITT

A frequent problem of LITT is that although it provides temperature changes in the tissue by MRI it does not provide the true extent of tissue damage [32]. Although LITT offers tighter thermal control than other minimally invasive techniques, there still remains a risk of hyperthermal damage to adjacent tissue, especially near areas without a heat sink such as CSF or vascular elements. Furthermore, in a review by Pruitt et al., hemorrhage occurred in up to 6.5% of patients who had LITT due to catheter insertion or removal [30]. Edema is commonly seen in LITT and is effectively managed with steroid treatment. However, in patients with large lesions, the edema may become symptomatic and/or refractory [23].

Development of stereotactic cryoablation

Hass and Taylor were the first to assess cryoablation in 1948. Cryoablation was then revolutionized and popularized by Cooper in 1963. Cooper described a cryogenic system that he and his associated developed, which utilized liquid nitrogen. Early trials of cryogenic surgery by Cooper were used for thalamotomy. He also performed cryosurgery on 12 patients with inoperable brain tumors. He concluded that cryosurgery is a simple, rapid, controllable, and safe method to treat neoplasms of the central nervous system [33, 34].

Cooper's work in cryosurgery created an explosion of interest in the use of cryoablation in neurosurgery in the early 1900s. Coe et al. questioned Cooper's research. Based on their own studies in cats, they concluded that the size and shape of the lesions produced by freezing are seldom predictable and do not correlate well with the temperatures of the probe tip [35]. Moser et al. sought out to further evaluate the study by Coe et al. and their conclusion. They perform cryoablation in four dogs using CT guidance. Cryoprobe tips were cooled in a stepwise manner to − 180 °C. A 2-cm-diameter ice ball was the maximum size that could be produced over an average time of 30 min. The results showed that ice ball production was well tolerated in all subjects with no immediate or delayed hemorrhage. Two subjects were maintained for 4 and 8 weeks and showed no evidence of neurologic dysfunction. Blood–brain barrier breakdown extended no more than 1 mm beyond the diameter of the ice ball. They concluded that CT guidance could be used to monitor ice ball formation in the brain, making it possible to precisely control the lesion size [36].

In a study by Maroon et al. in 1992, 71 patients with various brain neoplasms were studied, 64 of which underwent ultrasound-guided cryosurgical extraction and 7 of which underwent cryoablation. All intracranial, intraspinal, and intra-orbital tumors were completely removed in the patients who underwent ultrasound-guided cryosurgical extraction, and there was no evidence of recurrence in the seven patients who underwent cryoablation [37].

Modern CT-guided stereotactic cryoablation

Although cryoablation has been used to treat malignancy in a wide variety of organs, including the eye, brain, head/neck, and esophagus, in current practice it is most commonly used in the treatment of liver, kidney, lung, prostate, and breast malignancy. Cryosurgery was revolutionized by the introduction of argon–helium-based system in 1998. This new system ablates tumors by combining freezing and thawing mechanisms, which generate rapid temperature drops by the free expansion of gas that can be controlled precisely to produce a predictable zone of necrosis within the target lesion [38]. Furthermore, smaller diameter (1.5 and 2.4 mm) probes were also introduced. This reduced the risk of damage to the surrounding healthy tissues [38].

Mechanism of cryoablation

High-pressure argon gas is circulated through the lumen of thin probes because of its low viscosity. Low pressure within the lumen of the cryoprobe results in a rapid expansion of argon gas, which creates an exceptionally low temperature. This creates an ice ball at the active tip of the probe. Depending on the diameter and length of the active tip, and duration of exposure, the size of the ice ball varies. The smaller ice balls are roundish, while the larger ones are oblong. The length of the larger ice balls can be up to 4 cm. The temperature at the margin of the ice ball is 0 °C. Lethal temperatures (− 20 to − 50 °C) are found 5 mm inside the ice ball edge. Therefore, the ice ball needs to be extended beyond the tumor border for complete ablation. During freezing, extracellular ice formation leads to the sequestration of free extracellular water, increasing the osmolarity of the extracellular space. This results in cellular dehydration and shrinkage. Intracellular ice formation causes disruption of organelle and plasma membranes, which impairs cellular function. During thawing, extracellular ice melts first, creating an osmotic fluid shift of water into damaged cells, resulting in cellular swelling and bursting. Intracellular ice crystals continue to grow during thawing, which further exacerbates cellular damage. The thaw is mostly passive and slow, which maximizes cell death. Helium gas is circulated at the end of the thaw to accelerate cryoprobe removal. Damage to the vascular endothelium results in tissue edema. Delayed cellular damage occurs secondary to apoptosis that is triggered by cold-induced cellular injury. Thrombosis of blood vessels causes tissue ischemia, further slowing repair. Inflammatory cells, including macrophages and neutrophils, remove damaged cells and clear cellular debris [39].

Advantages of cryoablation

The primary advantage of cryoablation over thermal ablation techniques is the ability to monitor the ablation volume during the procedure in real time. During freezing, the water of the tissue undergoes a phase transition from liquid to solid, forming an ice ball, which is visible under ultrasound scan, CT imaging, and MRI. On intraoperative CT images, the ablation zone appears as a sharply demarcated hypoattenuating zone around the cryoprobe [39]. This clear demarcation is not seen with thermal ablation. Therefore, intraprocedural monitoring with CT imaging is necessary, to maximize the chance of complete ablation of the target and to minimize the chance of damage to the surrounding critical structures [40, 41]. Cryoablation also has the advantage that the active tip of the probe can be thawed immediately if needed. In addition, this procedure is performed in the CT room, because its use is readily available in most facilities, while it is not very practical to perform it in the MRI environment [42].

Safety

Vascular complications, such as hemorrhage or thrombus formation, are important complications of epilepsy surgery. The safety of cryoablation being performed adjacent to important vascular structures is well documented. This is in part due to its limited endothelial disruption when compared to other minimally invasive techniques. In a study by Khairy et al., cry lesions created near the coronary arteries of dogs were associated with less endothelial disruption and overlying thrombus formation when compared to RF lesions at the same depth. This allows for deeper lesion formation while minimizing damage to surrounding tissues. This study found that there is a 5.6-fold lower risk of thrombus formation with cryoablation than with RF ablation ($p = 0.0042$) [43]. The safety is further improved because ice ball formation can be observed on intraoperative scans, its volume can be controlled by adjusting the flow rate of argon while visualizing ice ball formation, and the probe tip can be emergently thawed [44]. Merkle et al. prospectively evaluated 18 patients who underwent gadolinium-enhanced MR imaging after RF ablation for solid renal tumors and found that the size of the RF ablation zone initially increases by approximately 10% within the first 2 weeks after ablation [45]. While hyperthermia-induced lesion sizes may increase within the first 10 days because of delayed heat effects, cryoablation zone volume does not expand after the cryoablation procedure, meaning that the lesion size is very predictable [46].

Lower complication rates have been seen with cryoablation when compared with radio frequency ablation in the treatment of renal cell cancer. In studies comparing outcomes in the treatment of small renal masses using cryoablation versus RF ablation, major complication rates were 1.8% in cryoablation patients versus 2.7% in RF ablation patients. Furthermore, the retreatment rate in cryoablation patients was 0.9% versus 8.8% in RF ablation patients [46].

Reduced pain

Cryoablation tends to be less painful than the heat-based thermal ablation techniques like microwave or radio frequency ablation [39]. In a study by Allaf et al., pain control requirements were compared between percutaneous treatments of cryoablation and RF ablation in patients with renal tumors. The cryoablation group was associated with a significantly lower dose of intravenous fentanyl (165 μg in RF group vs 75 μg in the cryoablation group, $p < 0.001$). Comparable results were held for doses of midazolam, and one patient in the RF group required general anesthesia [47]. A study by Timmermans et al. compared pain perception between cryoablation and RF ablation treatments in patients with atrial flutter. The proportion of painful applications averaged 75.3% in the RF group and 2.0% in the cryoablation group ($P < 0.05$), whereas the corresponding VAS for pain was 38.3 ± 25.3 and 0.32 ± 0.86, respectively ($P < 0.05$). They concluded that cryoablation produces significantly less pain than RF ablation during application [48].

Costs

CT-guided cryoablation is a widely accessible treatment modality given the wide availability of CT suites in most healthcare institutions. Not only is CT imaging readily available, but it is significantly less expensive compared to MRI imaging. In addition, the cryoablation machine does not need to be purchased; it is rented on a per-procedure basis. Furthermore, many cryoablation systems now utilize argon, which is inexpensive. This makes the total cost of cryoablation less than laser ablation [49].

Other advantages

Cryotherapy can also induce systemic therapeutic effects through cry immunology, such as ectopic tumor inhibitory effects [50]. Cryoablation has also been shown to produce antibodies to the ablated tumor antigen in both animals and humans. Furthermore, animal studies have shown that a tumoricidal cell-mediated immune response may be induced to a greater degree with cryoablation than with RF ablation. An explanation is that the combination of the increased inflammation and the larger degree of in situ tumor antigen with cryoablation results in greater antigen presentation by dendritic cells, eliciting a more robust T-cell-mediated antitumoral response [39].

Clinical outcomes using stereotactic cryoablation for brain tumor treatment

Brain tumors

In a study by Li et al., seven patients with cystic metastatic brain tumors underwent MRI-guided cryoablation using argon-based cryoablation system. All patients tolerated the procedure well without any neurological deficits. They concluded that MR-guided cryoablation of metastatic brain tumors is technically feasible and may represent an alternative treatment in selected patients [15]. In a study by Martynov et al., 88 patients with unresectable supratentorial gliomas underwent MRI-guided cryoablation using CO_2-based cryoablation system. Survival rates when compared to historical controls were shown to be 92.9% to 59.3% in patients with diffuse astrocytoma, 62.4% to 42.5% in patients with anaplastic astrocytoma, and 90.0% to 50.0% in patients with glioblastoma multiform. Complications were seen in 11.4% of patients. They concluded that postoperative survival was significantly associated with stereotactic cryo-destruction of the tumor ($p < 0.05$) and that stereotactic cryoablation in patients with unresectable supratentorial gliomas is a safe and potentially effective treatment modality [51].

In a recent study by Patil, three patients with large tumors underwent CT-guided cryoablation using argon-based cryoablation system. Patient 1 with 8 × 8 cm non-secreting pituitary adenoma yielded a reduction in tumor size to 6.7 × 5.1 cm and a resolution of headaches at 2 years. Patient 2 with 5.1 × 4.6 cm prolactinoma yielded a resolution of diplopia and improved vision within 24 h as well as a reduction in tumor size to 2.1 × 1.3 cm at 7 months. Patient 3 with 7.2 × 5 cm recurrent craniopharyngioma yielded a complete reduction in cyst and a resolution of all symptoms for 8 months, after which his headache and visual symptoms recurred due to new masses on the cyst wall [52].

Local recurrence

As mentioned previously, cryoablation procedures can be performed with multiple probes. This allows for complete coverage of the tumor and is especially beneficial in large tumors, in which other minimally invasive techniques may experience difficulty treating. In a study by Schmidt et al., it was shown that tumor size is not definitively associated with local recurrence after renal cryoablation. They were able to successfully perform percutaneous cryoablation in patients with renal masses > 3 cm without recurrence in any patients for an average follow-up of 15 months (range 3–42 months). A known limitation of RF ablation in renal tumors is the high local recurrence rate after treatment of tumors > 3 cm [53]. The above findings in conjunction highlight the benefits of real-time intraoperative visualization of the ice ball and complete tumor coverage provided by adjacent cryoablation probes. Other studies of small renal masses have also supported this finding, with rates of local recurrences and metastatic progression favoring cryoablation over RF ablation. Local recurrence rates are approximately 4.6% in cryoablation patients versus 11.7% in RF ablation patients. The metastatic progression rate is approximately 1.2% in cryoablation patients versus 2.3% in RF ablation patients [46].

Clinical outcomes using stereotactic cryoablation to treat intractable epilepsy

While there is a scarcity of data regarding the treatment of medically intractable epilepsy with stereotactic cryoablation, there is one study that has explored exactly that. In a study by Chkhenkeli et al., 21 patients with intractable bitemporal epilepsy underwent SEEG-guided bilateral asymmetrical cryoablation. 52% of patients achieved an Engel I outcome, 29% of patients achieved an Engel II outcome, and 19% of patients achieved an Engel IV outcome. No worsening of seizures or clinically significant cognitive or memory impairment was reported at a follow-up of 5–10 years. They concluded that stereotactic cryoablation of both temporal lobes can have a beneficial effect on seizure frequency and severity without declines in intelligence, learning, or memory [54]. This study showed similar seizure freedom rates to that of thermal ablation. However, the lack of clinically significant cognitive or memory impairment at 5–10-year follow-up is an incredible finding. It can be deduced that this is due to the safety that is conferred by superior intraoperative visualization.

Limitations of cryoablation

It should be recognized that there is a lack of data available for cryoablation performed in patients with medically intractable epilepsy. There is a need for randomized control trials comparing seizure outcomes between patients undergoing cryoablation and other minimally invasive techniques.

Ice ball fractures are a rare and unique complication of cryoablation that can result in hemorrhage. However, as stated previously, real-time visualization of the ice ball on CT allows the surgeon to readily identify ice ball fractures, allowing for prompt intervention should it be needed [2].

Conclusion

Although stereotactic cryoablation has lost its place in the field of neurosurgery, it still remains as an effective and safe treatment modality in other fields. When paired with CT-guided imaging, stereotactic cryoablation has the potential to outperform the other widely used minimally invasive surgical techniques in the treatment of intractable epilepsy. The intraoperative visualization conferred by CT-guided cryoablation is superior to that of thermal ablation due to the ability to clearly identify the ice ball margins. The ability to visualize the ablation zone in real time allows the surgeon to maximize the chances of complete tumor destruction while minimizing damage to surrounding healthy tissues. This subsequently results in lower complication rates, reduced pain, and shorter hospital stays as compared to thermal ablation. These characteristics are of the utmost importance in patients with medically intractable epilepsy, who could be avoiding any surgical interventions due to fear of complications. Furthermore, CT suites are widely available and are inexpensive in comparison with MRI. Randomized control trials are needed in the future in order to further investigate its benefits in patients with intractable epilepsy.

Abbreviations
CT: Computerized tomography imaging; MRI: Magnetic resonance imaging; AED: Antiepileptic drugs; MTLE: Mesial temporal lobe epilepsy; ATL: Anterior temporal lobectomy; SAH: Selective amygdalohippocampectomy; CSF: Cerebrospinal fluid; TLE: Temporal lobe epilepsy; LITT: Leer interstitial therapy; SLAH: Stereotactic laser amygdalohippocampotomy; SRS: Stereotactic radiosurgery.

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Consent for publication
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Competing interests
The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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