IMAGING AND INTERVENTION

REVIEW IMAGING AND INTERVENTION 2022;1(3):66-73
DOI: 10.5152/iai.2022.21024

Laser Ablation in Magnetic Resonance Imaging/Computed Tomography Environment: A Review

Aaron Asael Smith[1], Rui Li[2], Zion Tsz Ho Tse[3]

[1]University of Georgia College of Engineering, Athens, GA, USA
[2]New York University Tandon School of Engineering, Brooklyn, NY, USA
[3]Department of Electronic Engineering, University of York, Heslington, York, UK

Abstract

Laser ablation has become a rising minimally invasive method in place of surgical resection for the removal of tumors related to a range of problems from prostate and pulmonary cancers to high-grade gliomas and refractory epilepsy. Robotic and non-robotic approaches to laser ablation are compared. Research articles were collected from Google Scholar by topics of interest based on more recent findings, and only articles that contained accuracy measurements were included in this review. There are two pathways in the field of laser ablation: robotic and non-robotic approaches. The accuracy of robotic devices is 0.3-3 mm. The accuracy of non-robotic devices is 0.02-5.86 mm. Both types of devices generate similar targeting accuracy towards tumor removal. In addition, the patient safety of operating the laser ablation devices has also been summarized. It is concluded that robotic laser ablation is feasible and more accurate and efficient compared to other methods; however, further clinical testing is needed to establish the safety and accuracy in real-life scenarios as most results were extracted from non-respiratory environments.

Keywords: Laser ablation, MRI-guided, prostate cancer, robotics

Introduction

Laser ablation (LA) has become a rising minimally invasive method in place of surgical resection for the removal of tumors related to prostate cancer. The clinical application of lasers in surgical procedures was first investigated by Solon et al.[1] Later, this investigation began to divulge into the clinical testing for the application for prostate tumors in the 1980s.[2-4] Since the 2000s laser diodes (980 nm) emerged replacing Nd:YAG lasers due to their ability to obtain similar tissue penetration while being more portable and less expensive.[4,5] One of the difficulties with using LA early in its testing was the lack of monitoring the ablation progress; however, recently, there have been technological advancements providing intraoperative thermal monitoring paired with magnetic resonance imaging (MRI) capabilities.[6] The two most effective methods for non-invasive thermometry are MR- and computational tomography (CT)-based.

Magnetic resonance thermometry has been increasingly popular due to its accuracy for spatial and temporal resolution.[7] Neuroblate (Monteris Medical, Plymouth, Minn, USA) and Visualase (Medtronic, Minneapolis, Minn, USA) are two stereotactic Laser Interstitial Thermal Therapy (LITT) that are frequently used for ablations utilizing MRI capability differing in their laser-firing orientation and intraoperative mobility. These systems each have their own advantages depending on the size of the tumor regarding target conformality.[8] The main advantage of MR thermometry is the ability to produce a live 3-dimensional temperature map allowing the surgeon to analyze the results of the procedure during the ablation process. This, as a result, reduces the amount of damaged healthy tissue while decreasing the operation time. The most recent proposed therapy is the insertion of accumulated nanoparticles that are designed with a higher affinity for the near-infrared region (650-900 nm).[9] These nanoparticles would be absorbed and converted into heat, allowing the ablation procedure to be further controlled and focused on the target. The use of nanoparticles is still vastly early in its stages, and therefore, this article will focus primarily on the growing advancements and results from MR-/CT-guided LA without the use of nanoparticles.

Another newly developing method involved in the LITT procedure is the use of augmented (AR) and virtual reality (VR). Although these methods are not currently being used in the real-world clinical environment, these methods are being

Cite this article as: *Smith AA, Li R, Tsz Ho Tse Z. Laser ablation in magnetic resonance imaging/computed tomography environment: A review. Imaging Interv. 2022;1(3):66-73.*

Corresponding author: Zion Tsz Ho Tse email: zion.tse@york.ac.uk

Received: July 23, 2021 **Accepted**: January 22, 2022

experimented on to help provide preoperative preparation for those performing the procedure. Augmented reality integrates virtual images by superimposing them over a designated area of the lens. In effect, this has the potential to superimpose internal imaging of a patient to improve the surgeon's ability to navigate surgical procedures such as LITT and for preoperative planning. Vávra et al[10] suggest that it also improves the safety and efficacy of procedures like traditional techniques. Okamoto et al[11] described the use of AR in hepatobiliary surgery as useful with accurate overlaid organ images; however, problems of registration error and depth information were noted.[11] Virtual reality is an immersive virtual space that has the potential to design specific scenarios for practical experience. Angulo et al[12] designed a VR simulator for prostate LA and concluded that it provides a good learning model; however, the accuracy of the procedure depended heavily upon the surgeon's level of spatial orientation skills and experience—requiring a variable amount of learning period.[12]

Although LITT has not become a primary solution to the removal of all tumors, it still plays a significant role in many specific medical applications and needs. According to Hawasli et al[8] LA becomes the best default treatment for patients who are unable to undergo traditional surgical methods due to advanced age or other medical abnormalities. Hawasli et al[8] also stated that LITT has greater maneuverability making it easier to remove hard-to-reach tumors, thus in effect reducing surgical morbidities. In addition, LITT can be repeated with no hindrance to wound healing or effectiveness.[8] Other advantages of LITT, as described by Caruso et al[13] are the reduced perioperative blood loss due to minimal invasiveness, reduced frequencies of postoperative seizures and drop attacks, and reduced overall patient stay in the hospital.[13] Magnetic resonance imaging-guided focal LA (FLA) also reduces the magnitude of postoperative pain management.[14] With these things in mind, LA appears to have the potential to play a significant role in the removal of all tumors as it continues to develop.

Search Methods

Research articles were collected from Google Scholar by topics of interest based on more recent findings, especially for the use of VR/AR technology and ultrasound, which consisted of articles published at the latest by 2014. Previous MRI Robot articles from 2008 to 2018 were included in this study; three of the articles were from the past four years. Only articles that contained operation accuracy were included in this review.

Surgical Applications

Magnetic Resonance-Guided Surgical Operation

Magnetic resonance imaging is regarded as a non-invasive imaging technique that can deliver surgical images with high spatial resolution and multiplanar anatomical images with great contrast.[15] Also, it can monitor many physiological and functional parameters such as temperature. All the features mentioned makes MRI a very versatile diagnostic modality in a surgical operation. Some of the main challenges of using MRI are the development of MR-compatible surgical instruments using nonferromagnetic materials. Image artifacts associated with different MR-compatible instruments have been elaborated in past literature.[16,17] One particular future direction could be to moderate the image artifacts, which can be used for device visualization and guidance.[18]

The MRI-guided procedure normally requires anesthesia. Natarajan et al[19] provide data stating that the average procedure time is 95 minutes utilizing local anesthesia under minimal sedation. Fusion of MRI-US and temperature monitoring were used, and it was determined that FLA be a feasible, efficient, and safe procedure noting no adverse events beyond grade 3 with 10 of 11 patients successfully treated.[19]

Chen et al[20] focused on MRI-guided FLA by developing an MRI-safe needle guidance robot providing two Degrees of Freedom (DoF) for the LA catheter and an optical encoder for its pneumatic turbine motors (Figure 1A). The concept with this design is to allow patients to remain inside the MRI bore, allowing for a decrease in operation time and more accurate live thermometry readings during the procedure. OncoNav (Onco, Inc., Wall Township, NJ, USA) was integrated, providing vital planning and monitoring of data to ensure complete ablation of the tumor. Cadavers and phantoms were utilized to obtain accuracy reports of 0.9 ± 0.4 mm with a maximum error of 1.6 mm and a minimum error of 0.3 mm—comparable to other known robotic devices while improving the mean and standard error of the traditional manual targeting approach suggested being 6.5 mm and 3.5 mm, respectively. Concluding the operation, it was noted to take approximately 100 minutes for the entire procedure, with three administrations leading to successful ablation.[20]

Seifabadi et al[21] proposed a solution that incorporates said needs through a system of robot and software that fits within an MR scanner and accurately guides the catheters to the prostate, proposing to enable greater accuracy and DoFs for larger prostates and a more optimized workflow from planning to the end of the procedure (Figure 1B). All materials used in this system are MRI safe and mainly consist of a pneumatic-based robotic guidance unit with a data acquisition card and encoder. The design of this system allows for variations of patient size and manual y-axis rotation specialized for behind urethra targeting. Free-space accuracy was 0.38 ± 0.27 mm. The overall system targeting accuracy under CT guidance (including robot, registration, and insertion error) was 2.17 ± 0.47 mm.[21]

Goldenberg et al[22] presented results of less than 2 mm of robot tip placement error when closer than 0.5 mm from the epicenter concluding that this device has the potential for treating prostate cancer.[22] Koethe et al[23] provided evidence for an increase of needle accuracy using a robotic Interventional Radiology (IR) assistance platform that resulted in $P < .0001$ for needle tip-to-target accuracy and $P = .03$ for residual target comparative to that of the freehand technique (Figure 1C). It was observed that needle accuracy and probe geometry were improved using the robotic IR assistance platform.[23] Bostrom et al[24] discovered 3 mm of target error with their MR-compatible robot. Ablation results were greater than 90% destruction utilizing a motorized trajectory alignment unit allowing for complex movements.[24] Moreira et al[25] presented 1.84 mm of average targeting error for their MR-conditional robot aimed for prostate interventions. The robot has 9 degrees of freedom allowing for the steering, rotation, and firing of the biopsy needle.[25] Yiallouras et al[26] developed an MRI-conditional robot compatible with a high-intensity focused ultrasound (HIFU) system that operated successfully in a 1.5-T MRI system using gel phantoms (Figure 1D). This device can provide controlled thermal lesions using MRI guidance for treating prostate cancer transrectally. A 20 μm linear axis and 0.11° angular axis measurement

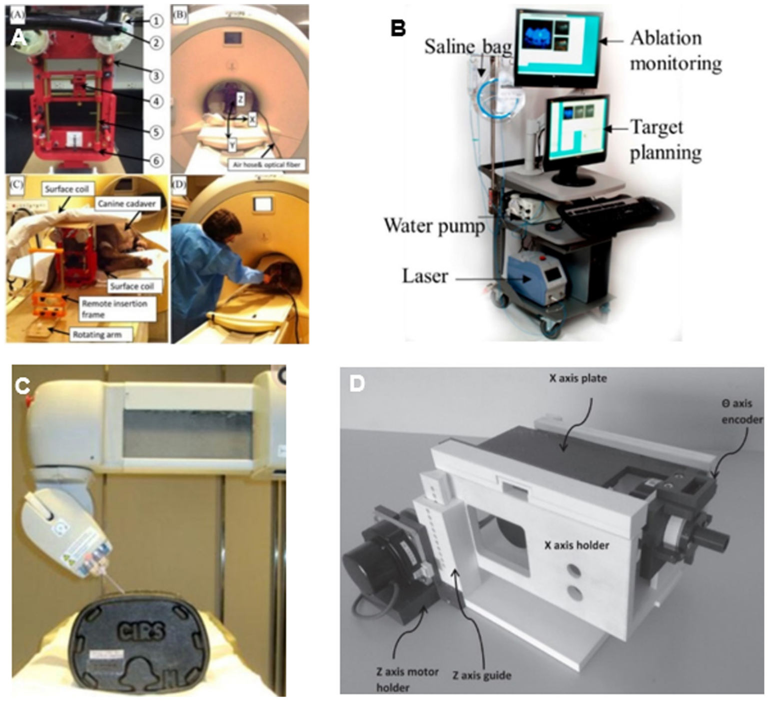

Figure 1. (A) MRI-conditional robot proposed by Chen et al. (B) MRI-fitted ablation device proposed by Seifabadi et al. (C) Robotic arm proposed by Koethe et al and robotic system used by Koethe et al. (D) MR-conditional robot for high-intensity focused ultrasound. An MRI-guided ultrasound-compatible robot proposed by Yiallouras et al. MRI, magnetic resonance imaging.

errors were observed, thus proving its accuracy and prospects in a clinical environment.[26] Cepek et al[27] demonstrated the feasibility of focal therapy using MRI-guided system. The targeting error for needles from the phantom study is 2.64 mm.

Computed Tomography-Guided Surgical Operation

Computed tomography is another modality that can provide detailed structural and functional images for surgical planning. Computed tomography-guided LA is an iterative, incremental advancement in medical instrumentation, which can track and navigate the area of interest before applying the instrument to the desired targets. One drawback of the CT-guided procedure is that it uses ionizing radiation that may cause safety issues for patients.[28] Also, it is not sensitive to changes in temperature, diffusion coefficients, or perfusion like MRI. Compared to MRI, CT is less capable of providing detailed information such as the lesion boundaries or margins. One of the current trends is to use CT together with positron emission tomography (PET) for dynamic monitoring of disease conditions. Previous studies have shown superior accuracy of ^{11}C-choline-PET/CT images compared to MRI for delineating intraprostatic lesions (IPLs).[29,30]

Dimmick et al[31] provided experimental accuracy results of CT-guided needle placement in a phantom, stating that after intervals of 5 performed procedures, the average error decreased by 0.33°. This study was aimed to illustrate the effectiveness of CT-guided needle placement training for potential applications such as LA for prostate cancer. Won et al[32] proposed a robot utilizing CT-guided intervention and procured an overall trajectory error of 2 mm (0-2.6 mm). Heerink et al[33] compared CT-guided ablation positioning between robotic antenna placement and freehand with promising results of 5.9 mm ± 2.9 robotic error and 10.1 mm ± 4.0 freehand error for out-of-plane targets.

Ultrasound-Guided Surgical Operation

Ultrasound has been widely applied in the field of interventional radiology as another non-invasive way to obtain real-time images with relatively low operating costs.[34] US is normally used for a standard procedures concerning peripheral joints.[35] However, the contrast of the scanned images is lower than both MRI and CT. One of the future directions is to combine US with MRI.[36-38]

Galgano et al[39] provided critical information for the treatment of prostate cancer using MR-guided high-intensity transurethral directional ultrasound (HIDU). The significance of the work provided suggests the ability to preserve critical tissues and outline boundaries into any ablation zone shape using transurethral HIDU. This paves the way to utilize this technology not only focally but also for the whole gland. The spatial targeting accuracy was found to be −1.0 mm ± 2.6, and HIDU was found to be able to treat large glands which its counterpart HIFU struggles with at the cost of setup time. Due to its design, it is not compatible with all MRI machines, requiring the use of 1.5- and 3.0-Tesla MRI scanners that have the needed software.[38]

Boctor et al[40] found approximately 3 mm of error for their dual-arm robotic US system including 0.8 mm attributed to US calibration and 2.54 mm for sensor uncertainty. An et al[41] developed a HIFU ablation robotic system that adjusts its trajectory accounting for the live movement of a patient when breathing. They found positioning error to be 1.72 ± 1.26 mm for single-point tracking and 3.04 ± 1.24 mm for cross-section ablation.[41] Daunizeau et al[42] designed an US-guided HIFU ablation navigation platform that rendered 4 ± 5% tumor volume estimation error while stating that conformal ablations can occur if tumor radii were ≤ 24 mm.

Augmented Reality for Interventional Oncology

Atashzar et al[43] discussed the principle of sensory and motor augmentation and its direct application with surgical procedures as being effective. Utilizing these concepts for robotic surgery has the potential to improve the surgeons' awareness of tissue interaction as well as provide corrective forces for improved outcomes.[43]

Solbiati et al[44] assessed the use of AR for oncology interventions using a tablet, markers, and a needle handle (Figure 2A). The assessment consisted of 3 models over which system accuracy was tested: (1) an anthropomorphic phantom with 5 polyvinyl chloride bars for non-respiratory motion; (2) the porcine model with metallic targets for respiratory motion; and (3) a cadaver with liver metastasis. This research discovered high targeting accuracy: 2.0±1.5 mm (for anthropomorphic phantom), 3.9±0.4 mm (for the porcine model), 2.5 mm and 2.8 mm (2 metastases in the cadaver model). These results indicate the advantage of using AR due to its ability to increase targeting accuracy while being able to visually see reconstructed internal structures normally not visible.[44]

Hecht et al[45] proposed an accuracy assessment for the use of AR needle guidance (Figure 2B). The AR was provided by a smartphone application with which 11 operators performed single-pass needle insertions. A needle insertion error of 2.69±2.61 mm was observed being 78% less compared to the traditional CT-guided freehand method. Li et al[46] developed an AR platform from both a smartphone and smart glasses to compared needle placement accuracy in percutaneous needle interventions. Target overlay error of 1.75±0.59 mm (smartphone), 1.74±0.86 mm (smart glasses), and needle placement error of 2.58± 1.04 mm (smartphone), 3.61 ± 2.25 mm (smart glasses) were observed. Kanithi et al[47] presented an AR system that provides needle trajectory visualization to aid in needle intervention. The average deviation of the needle trajectory was found to be 3.27 mm proving the accuracy of this concept to reduce the number of needle adjustments. Prakosa et al[48] proposed an evaluation of catheter navigation accuracy using AR ventricular tachycardia (VT) ablations. A navigation error of 2.96 ± 1.63 mm was observed for one of the silico-induced VTs; however, the other VT showed no significant difference in navigation accuracy. Li et al[49] presented an AR guidance system to improve liver tumor punctures under respiratory motion (Figure 2C). A range of 2.06-3.48 mm accuracy error within 2 adjustments was discovered, showing an increase of accuracy and efficiency compared to traditional CT-guided methods.[49]

Patient Safety Evaluation of Laser Ablation

Kamath et al[50] presented results on MRI-guided LITT, they performed 58 LITT treatments for glioblastoma (GBM) in 54 patients over 5.5 years. Forty-one were recurrent tumors, while 17 were frontline treatments. Forty GBMs were lobar in location, while 18 were in deep structures (thalamus, insula, and corpus callosum). There were 7 perioperative complications (12%) and 2 mortalities (3.4%). Median overall survival after LITT for the patients were 11.5 months with a median progression-free survival of 6.6 months.

Pech et al[51] provided results on MR-guided Interstitial Laser Thermotherapy (ILT) of colorectal liver metastases. Sixty-six patients with a total of 117 metastases were treated (40.9% rectum carcinoma, 30.3% sigmoid carcinoma, and 28.8% colon carcinoma) and were followed up on an average of 11.8 months. The median progression-free survival was 6.1 months, median survival was 23 months, rate of major complications was 2.1%, and periprocedural mortality was 3%. Local tumor control was found to be 98.3%, 91.4%, 76.1%, and 69.4% after intervals of 3 months over a 12-month period.

Rennert et al demonstrated results and procedural safety of Stereotactic laser ablation (SLA) of intracranial lesions. About 81.2% of patients had previous surgical/radiation treatments, and 79% of patients had a single lesion ablation after a lesion biopsy. Of the treated lesions, 72% had over 90% lesion ablation. A total of 5 adverse events were found to be related to SLA out of 100 events, with 1 mortality unrelated to SLA. About 84.8% of patients were discharged home. They discovered that the average length of hospital stay for using Neuroblate (Monteris Medical) for LA was 61.1 ± 87.2 h, which is comparable if not shorter than the average hospital stay for open cranial surgery. As a result, this reduces hospital costs.[52] Caruso et al[13] stated that they observed a reduced amount of blood loss, ICU stay, and hospital stay, attributing to the relatively fast recovery time.

Discussion

Laser ablation has shown a promising future as it is proved to be feasible and safe.[53] So far, the clinical potential of laser microsurgery has barely begun to be realized, with limited medical applications. There are 2 major approaches in the field of laser ablation: robotic and non-robotic methods. The accuracy of robotic surgery ranges from 0.3 to 3 mm. The non-robotic methodology accuracy ranges from 0.02 to 5.86 mm. Therefore, both approaches produce similar clinical outcomes.

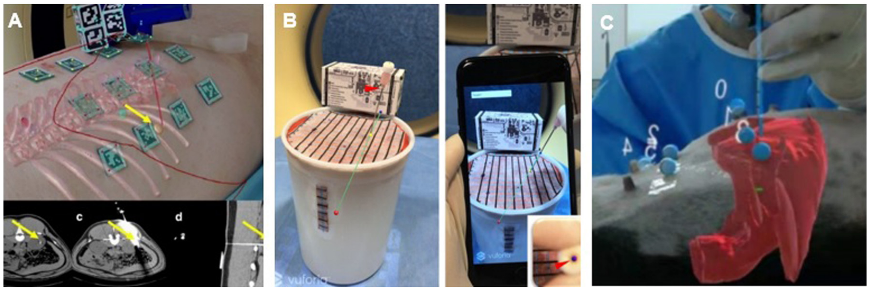

Figure 2. (A) Porcine model with augmented reality (AR) during needle insertion. Smartphone-enabled AR needle guidance proposed by Solbiati et al. (B) smartphone displays an aligned needle. Augmented reality-enabled interventional oncology proposed by Hecht et al. (C) AR guidance system for liver tumor puncture. Augmented reality-enabled guidance system proposed by Li et al for needle puncture.

Table 1. Previous Work on MRI/CT-Guided Robot for Laser Ablation

Research Groups	Modalities	Experimental Results	Applications	Pros and Cons	References
Chen et al	Focal laser ablation	The obtained accuracy is 0.9 ± 0.4 mm	Prostate cancer	N/A	[20]
Seifabadi et al	Focal laser ablation	The overall system targeting accuracy under CT guidance (including robot, registration, and insertion error) was 2.17 ± 0.47 mm	Prostate cancer	The new robot can accurately facilitate fiber targeting for MR-guided focal laser ablation of targetable prostate cancer	[21]
Goldenburg et al	Prostatic interventions (laser ablation)	The robot tip position error is less than 0.5 mm	Prostate cancer	Results are promising for application as a minimally invasive procedure for prostate cancer	[22]
Koethe et al	CT-guided biopsy and percutaneous ablation	Reduced mean needle tip-to-target error ($P < .0001$). Reduced residual tumor percentage ($P = .02$)	Clinical CT-guided biopsy and Radiofrequency ablation (RFA)	IR assistance platform can improve the accuracy of needle insertions and target ablation coverage	[23]
Bostrom et al	Focal laser ablation	The target error is 3 mm	Prostate cancer	Safe performance of laser ablation with increased targeting and insertion accuracy	[24]
Moreira et al	MR-guided interventions	The average targeting error is 1.84 mm	Prostate cancer	Demonstrates ability to perform MR-guided needle interventions with accuracy	[25]
Yiallouras et al	MR-guided HIFU ablation	20 μm error for linear axis and 0.11° for angular axis	Prostate cancer	Controlled thermal lesions using MRI guidance; very accurate	[26]
Cepek et al	Focal laser ablation	The targeting error for needle guides in the MRI bore is 1.71 mm. The targeting error for needles in phantom is 2.64 mm	Prostate cancer	Needle deflection increased error in phantom testing; however, the procedures were still effective and efficient	[27]
Dimmick et al	CT-guided need placement	Average error decreased by 0.33°	Prostate cancer	Demonstrates the ease and effectiveness of CT-guided needle placement training	[31]
Won et al	CT-guided laser ablation	Overall trajectory error: 2 mm (0-2.6 mm)	Prostate cancer	Accurate use of robotic CT-guided laser ablation	[32]
Heerink et al	CT-guided laser ablation	5.9 mm ± 2.9 robotic error and 10.1 mm ± 4.0 freehand error for out-of-plane targets	Liver cancer with prostate cancer applicability	Demonstrates the improved accuracy of robotic CT-guided laser ablation vs. freehand methods	[33]
Galgano et al	MR-guided HIDU ablation	Spatial targeting accuracy is 1.0 ± 2.6 mm	Prostate cancer	Transurethral HIDU allows for MRI-guided ablation of the prostate gland with the ability to contour boundaries and spare critical structures, such as the neurovascular bundle and urinary sphincter	[39]
Boctor et al	US-guided hepatic ablation	Approximately 3 mm of error (0.8 mm to US calibration and 2.54 mm for sensor uncertainty)	Liver cancer With prostate cancer applicability	Allows for robotic control of ultrasound manipulation and needle guidance which improves accuracy mitigating freehand error	[40]
An et al	US-guided robotic HIFU ablation	Positioning error: 1.72 ± 1.26 mm for single-point tracking and 3.04 ± 1.24 mm for cross-section ablation	Prostate cancer/tumors	Adjusts its trajectory accounting for the live movement of a patient when breathing	[41]
Daunizeau et al	US-guided HIFU ablation	4 ± 5% tumor volume estimation error	Any tumor-related illness (prostate cancer)	Useful for developing other HIFU approaches. Able to obtain accurate tumor volume estimation for the ablation procedure	[42]

CT, computed tomography; HIFU, high-intensity focused ultrasound; HIDU, high-intensity transurethral directional ultrasound; MRI, magnetic resonance imaging.

Table 2. Non-Robotic Medical Devices for Laser Ablation Applications

Research Groups	Modalities	Experimental Results	Applications	Pros and Cons	References
Solbiati et al	AR-guided interventional oncology	2.0±1.5 mm (phantom model); 3.9±0.4 mm (porcine model); 2.5 mm and 2.8 mm (2 metastases in the cadaver model)	Interventional procedures for tumor removal	AR provides great targeting accuracy for needle guidance while visualizing the internal structures	[44]
Hecht et al	Smartphone AR-guided CT-based intervention	The needle insertion error is 2.69±2.61 mm	Percutaneous biopsies and ablations	Reduced insertion error by 78% and operation time by 66% compared to CT-guided freehand methods	[45]
Li et al	Smartphone & Smartglasses AR-guided based interventions	The needle placement error is 2.58± 1.04 mm (smartphone), 3.61± 2.25 mm (smart glasses)	Percutaneous needle interventions	Noticeably reduced placement error compared to CT-guided freehand methods	[46]
Kanithi et al	AR-guided system-based ultrasound-guided intervention	The average error is ± 3.27 mm	Ultrasound-guided intervention	The camera must be orthogonal to the market for better tracking accuracy. Able to improve the accuracy of needle placement	[47]
Prakosa et al	AR-guided VT ablation	The navigation error is 2.96 ± 1.63 mm	Ventricular tachycardia	Improved accuracy of navigation and improved VT termination in I-type VT	[48]
Li et al	AR-guided radiofrequency ablation using Hololens (Microsoft, Albuquerque, NM, USA)	The target error is in the range of 2.06-3.48 mm	Liver cancer	Improved accuracy and reduction of needle adjustments	[49]

AR, augmented reality; CT, computed tomography; VT, ventricular tachycardia.

One of the technological barriers to the adoption of this technology is the lack of a means to flexibly deliver the laser light to clinical sites in or on the patient. Also, a common issue with using LA is the potential damage of normal tissue structure near the tumor when administering the treatment. Therefore, the amount of thermal energy applied to the tumor mass has to be precisely controlled. Moreover, inhomogeneous tissue architecture, the composition of tissue masses, and the inconsistent distribution of blood vessels will increase the complication of the ablation environment. One possible solution is to continuously monitor the temperature change. By considering both the tissue temperature map and the laser exposure time, real-time tissue temperature monitoring could be particularly beneficial for laser optimization during cancer treatment. For example, the LITT for brain tumors has the capability to visualize real-time temperature changes in deep-seated tumors.[54] One of the most promising non-invasive thermometric methods is MR-based thermometry. During LITT, MRI thermometry is used to identify the areas of energy absorption and tissue destruction. Therefore, neurosurgeons can visualize the area of tumor undergoing cell necrosis. After applying LITT, the metabolic activity of tumor volume will be evaluated by ^{11}C-methionine PET.

Another emerging solution is the use of nanoparticles in the laser ablation of cancer. Nanoparticles combined with ablation procedures is being considered as a promising approach to minimize healthy tissue damage because nanomaterials can selectively and specifically bind to the targeted region and increase its heating temperature. Nanoparticles could offer beneficial optical and magnetic properties by elevating and increasing the heat of the treated region.

The size, cost, robustness, and efficiency of laser systems have been improved significantly since their invention, particularly in the case of fiber lasers. In the future, more technologies could be incorporated into the development of new laser ablation devices. Virtual Reality and AR provide physicians alternative ways to visualize the real-time procedure. Virtual reality relies on purely virtual environments, AR "allows the user to see the real world, with virtual objects superimposed upon or composited with the real world."[55-56] Both modalities are used for clinical purposes by enabling the presentation of additional information pre- and intraoperatively.

In addition, clinical trials involving the use of single-/multi-armed robotic devices for performing this procedure are lacking. More clinical trials are needed to allow these devices entry into the clinical environment for patient care.

Radiologists have a vital role in LITT being the trained experts on medical imaging such as the MRI and CT imaging methods described. Interventional radiologists help identify the tumor location, ablation tool location, and results from the procedure through advanced medical imaging. Both surgeons and radiologists work together to help plan efficient and effective minimally invasive procedures to remove tumors. Often, the trained interventional radiologists perform the ablation process alone.[57]

On the side of clinical trial progress, Bostrom et al[24] provided MRI-guided clinical results of 2 patients who underwent FLA for prostate tumor removal and reported that for both cases, the laser was within 3 mm of the target. They also reported more than 90% tumor destruction with the patient discharged on the same day and without complications during or post-operation.

For CT-guided devices, Heerink et al[33] performed 31 clinical trials with mean patient age of 63 years old with a total of 47 assessed liver tumors. They noted that antenna repositioning was not required for their robotic arm procedure, improving the ablation efficacy. As previously noted, out-of-plane targeting errors for their robotic guidance were 40% lower compared to freehand. In their trials, general anesthesia and vacuum mattresses were used to attempt to eliminate motion. A problem with average targeting time was noted, with approximately 17 additional average minutes for targeting. No post-operation patient outcome results were noted.

Galgano et al[39] presented early clinical trials of transurethral HIDU where all 8 patients were operated on for an average of 3 hours in a 1.5-T MR scanner. They observed that HIDU was tolerable for all patients and had high targeting accuracy, as noted prior, suggesting the safety and feasibility of this procedure. Their single-arm clinical trial of 30 low-intermediate risk patients with prostate cancer observed 36 minutes of treatment time and similar targeting accuracy as observed in the previous trials. They also made note that according to the Common Terminology Criteria for Adverse Events, 50% of patients had side effects of hematuria, 33% urinary tract infection, 27% acute urinary retention, and 3.3% epididymitis; however, despite these side effects, it was concluded that this procedure was feasible and safe.

Conclusion

Laser ablation has become a rising minimally invasive method in place of surgical resection for the removal of tumors related to a range of problems from prostate and pulmonary cancers to high-grade gliomas and refractory epilepsy. Recent technological advancements provide intraoperative thermal monitoring paired with MRI capabilities. With all things considered, LA appears to have the potential to play a significant role in cancer tumor removal.

It is concluded that robotic LA is feasible and more accurate and efficient compared to other methods; however, further clinical testing is needed to establish the safety and accuracy in real-life scenarios as most results were extracted from non-respiratory environments. The technological advancement of LA appears to be promising as further testing and improvements are made, opening this to be a primary clinical supported treatment for patients.

Peer Review: Externally peer-reviewed.

Author Contributions: Concept – A.S., R.L.; Design – A.S., R.L.; Supervision – Z.T.; Resources – Z.T.; Materials – A.S., R.L.; Data Collection and/or Processing – A.S.; Analysis and/or Interpretation – A.S., R.L.; Literature Search – A.S., R.L.; Writing Manuscript – A.S., R.L.; Critical Review – A.S., R.L.

Acknowledgment: The images in the article are original work or have been used after getting permission from the original source.

Declaration of Interest: The authors have no conflict of interest to declare.

Funding: This study received no funding.

References

1. Solon LR, Aronson R, Gould G. Physiological implications of laser beams. *Science*. 1961;134(3489):1506-1508. [CrossRef]
2. Bown SG. Phototherapy of tumors. *World J Surg*. 1983;7(6):700-709. [CrossRef]
3. Muschter R, Hofstetter A. Interstitial laser therapy outcomes in benign prostatic hyperplasia. *J Endourol*. 1995;9(2):129-135. [CrossRef]
4. Schena E, Saccomandi P, Fong Y. Laser ablation for cancer: past, present and future. *J Funct Biomater*. 2017;8(2). [CrossRef]
5. Zukiwskyj M, Daly P, Chung E. Penile cancer and phallus preservation strategies: a review of current literature. *BJU Int*. 2013;112(suppl 2):21-26. [CrossRef]
6. Saccomandi P, Schena E, Silvestri S. Techniques for temperature monitoring during laser-induced thermotherapy: an overview. *Int J Hyperthermia*. 2013;29(7):609-619. [CrossRef]
7. Todd N, Diakite M, Payne A, Parker DL. In vivo evaluation of multi-echo hybrid PRF/T1 approach for temperature monitoring during breast MR-guided focused ultrasound surgery treatments. *Magn Reson Med*. 2014;72(3):793-799. [CrossRef]
8. Hawasli AH, Kim AH, Dunn GP, Tran DD, Leuthardt EC. Stereotactic laser ablation of high-grade gliomas. *Neurosurg Focus*. 2014;37(6):E1. [CrossRef]
9. Huang X, El-Sayed IH, Qian W, El-Sayed MA. Cancer cell imaging and photothermal therapy in the near-infrared region by using gold nanorods. *J Am Chem Soc*. 2006;128(6):2115-2120. [CrossRef]
10. Vávra P, Roman J, Zonča P, et al. Recent development of augmented reality in surgery: a review. *J Healthc Eng*. 2017;2017:4574172. [CrossRef]
11. Okamoto T, Onda S, Matsumoto M, et al. Utility of augmented reality system in hepatobiliary surgery. *J Hepato-Bil Pancreat Sci*. 2013;20(2):249-253. [CrossRef]
12. Angulo JC, Arance I, García-Tello A, et al. Virtual reality simulator for training on photoselective vaporization of the prostate with 980nm diode laser and learning curve of the technique. *Actas Urol Esp*. 2014;38(7):451-458. [CrossRef]
13. Caruso JP, Janjua MB, Dolce A, Price AV. Retrospective analysis of open surgical versus laser interstitial thermal therapy callosotomy in pediatric patients with refractory epilepsy. *J Neurosurg Pediatr*. 2021;27(4):420-428. [CrossRef]
14. Wenger H, Yousuf A, Oto A, Eggener S. Laser ablation as focal therapy for prostate cancer. *Curr Opin Urol*. 2014;24(3):236-240. [CrossRef]
15. Liu H, Hall WA, Martin AJ, Maxwell RE, Truwit CL. MR-guided and MR-monitored neurosurgical procedures at 1.5 T. *J Comput Assist Tomogr*. 2000;24(6):909-918. [CrossRef]
16. Haji-Valizadeh H, Rahsepar AA, Collins JD, et al. Validation of highly accelerated real-time cardiac cine MRI with radial k-space sampling and compressed sensing in patients at 1.5 T and 3T. *Magn Reson Med*. 2018;79(5):2745-2751. [CrossRef]
17. Yang F, Dogan N, Stoyanova R, Ford JC. Evaluation of radiomic texture feature error due to MRI acquisition and reconstruction: a

simulation study utilizing ground truth. *Phys Med*. 2018;50:26-36. [CrossRef]
18. Li R, Xu S, Bakhutashvili I, et al. Template for MR visualization and needle targeting. *Ann Biomed Eng*. 2019;47(2):524-536. [CrossRef]
19. Natarajan S, Jones TA, Priester AM, et al. Focal laser ablation of prostate cancer: feasibility of magnetic resonance imaging-ultrasound fusion for guidance. *J Urol*. 2017;198(4):839-847. [CrossRef]
20. Chen Y, Xu S, Squires A, et al. MRI-guided robotically assisted focal laser ablation of the prostate using canine cadavers. *IEEE Trans Bio Med Eng*. 2018;65(7):1434-1442. [CrossRef]
21. Seifabadi R, Li M, Xu S, et al. MRI robot for prostate focal laser ablation: an ex vivo study in human prostate. *J Imaging*. 2018;4(12):140. [CrossRef]
22. Goldenberg AA, Trachtenberg J, Kucharczyk W, et al. Robotic system for closed-bore MRI-guided prostatic interventions. *IEEE/ASME Trans Mechatron*. 2008;13(3):374-379. [CrossRef]
23. Koethe Y, Xu S, Velusamy G, Wood BJ, Venkatesan AM. Accuracy and efficacy of percutaneous biopsy and ablation using robotic assistance under computed tomography guidance: a phantom study. *Eur Radiol*. 2014;24(3):723-730. [CrossRef]
24. Bostrom PJ, Davidson SRH, Lindner U, et al. First clinical experience with robotic MR-guided focal laser ablation of prostate cancer. *J Urol* 2011. 1301;185(4S):e520-e521. [CrossRef].
25. Moreira P, Steeg Gvd, Krabben T, et al. The MIRIAM Robot: a novel robotic system for MR-guided needle insertion in the prostate. *J Med Robot Res*. 2017;2(4). [CrossRef]
26. Yiallouras C, Ioannides K, Dadakova T, Pavlina M, Bock M, Damianou C. Three-axis MR-conditional robot for high-intensity focused ultrasound for treating prostate diseases transrectally. *J Ther Ultrasound*. 2015;3:2. [CrossRef]
27. Cepek J, Chronik BA, Lindner U, et al. A system for MRI-guided transperineal delivery of needles to the prostate for focal therapy. *Med Phys*. 2013;40(1):012304. [CrossRef]
28. Goodman TR, Mustafa A, Rowe E. Pediatric CT radiation exposure: where we were, and where we are now. *Pediatr Radiol*. 2019;49(4):469-478. [CrossRef]
29. Yamaguchi T, Lee J, Uemura H, et al. Prostate cancer: a comparative study of 11C-choline PET and MR imaging combined with proton MR spectroscopy. *Eur J Nucl Med Mol Imaging*. 2005;32(7):742-748. [CrossRef]
30. Testa C, Schiavina R, Lodi R, et al. Prostate cancer: sextant localization with MR imaging, MR spectroscopy, and 11C-choline PET/CT. *Radiology*. 2007;244(3):797-806. [CrossRef]
31. Dimmick S, Jones M, Challen J, Iedema J, Wattuhewa U, Coucher J. CT-guided procedures: evaluation of a phantom system to teach accurate needle placement. *Clin Radiol*. 2007;62(2):166-171. [CrossRef]
32. Won HJ, Kim N, Kim GB, Seo JB, Kim H. Validation of a CT-guided intervention robot for biopsy and radiofrequency ablation: experimental study with an abdominal phantom. *Diagn Interv Radiol*. 2017;23(3):233-237. [CrossRef]
33. Heerink WJ, Ruiter SJS, Pennings JP, et al. Robotic versus freehand needle positioning in CT-guided ablation of liver tumors: a randomized controlled trial. *Radiology*. 2019;290(3):826-832. [CrossRef]
34. Halpern EJ. Contrast-enhanced ultrasound imaging of prostate cancer. *Rev Urol*. 2006;8(suppl 1):S29-S37.
35. Xu G, Rajian JR, Girish G, et al. Photoacoustic and ultrasound dual-modality imaging of human peripheral joints. *J Biomed Opt*. 2012;18(1):010502.
36. Valerio M, Donaldson I, Emberton M, et al. Detection of clinically significant prostate cancer using magnetic resonance imaging–ultrasound fusion targeted biopsy: a systematic review. *Eur Urol*. 2015;68(1):8-19. [CrossRef]
37. Pinto PA, Chung PH, Rastinehad AR, et al. Magnetic resonance imaging/ultrasound fusion guided prostate biopsy improves cancer detection following transrectal ultrasound biopsy and correlates with multiparametric magnetic resonance imaging. *J Urol*. 2011;186(4):1281-1285. [CrossRef]
38. Xu S, Kruecker J, Turkbey B, et al. Real-time MRI-TRUS fusion for guidance of targeted prostate biopsies. *Comput Aided Surg*. 2008;13(5):255-264. [CrossRef]
39. Galgano SJ, Planz VB, Arora S, Rais-Bahrami S. MR-guided high-intensity directional ultrasound ablation of prostate cancer. *Curr Urol Rep*. 2021;22(1):3. [CrossRef]
40. Boctor EM, Fischer G, Choti MA, Fichtinger G, Taylor RH. A dual-armed robotic system for intraoperative ultrasound guided hepatic ablative therapy: a prospective study. In: IEEE International Conference on Robotics and Automation, 2004. Proceedings ICRA '04, vol. 2004, 26 April-1 May, 2004.
41. An CY, Hsu YL, Tseng CS. An ultrasound-guided robotic HIFU ablation system with respiration induced displacement and time delay compensation. *J Med Biol Eng*. 2019;39(5):796-805. [CrossRef]
42. Daunizeau L, Nguyen A, Le Garrec M, Chapelon JY, N'Djin WA. Robot-assisted ultrasound navigation platform for 3D HIFU treatment planning: initial evaluation for conformal interstitial ablation. *Comput Biol Med*. 2020;124:103941. [CrossRef]
43. Atashzar SF, Naish M, Patel RV. Active sensorimotor augmentation in robotics-assisted surgical systems. In: *Mixed and Augmented Reality in Medicine*. Boca Raton: CRC Press; 2019:61-81.
44. Solbiati M, Passera KM, Rotilio A, et al. Augmented reality for interventional oncology: proof-of-concept study of a novel high-end guidance system platform. *Eur Rad Exp*. 2018;2(1):18. [CrossRef]
45. Hecht R, Li M, de Ruiter QMB, et al. Smartphone augmented reality CT-based platform for needle insertion guidance: a phantom study. *Cardiovasc Intervent Radiol*. 2020;43(5):756-764. [CrossRef]
46. Li M, Seifabadi R, Long D, et al. Smartphone-versus smartglasses-based augmented reality (AR) for percutaneous needle interventions: system accuracy and feasibility study. *Int J Comput Assist Rad Surg*. 2020;15(11):1921-1930. [CrossRef]
47. Kanithi PK, Chatterjee J, Sheet D. Immersive augmented reality system for assisting needle positioning during ultrasound guided intervention. In: *Proceedings Tenth Indian Conference on Computer Vision, Graphics and Image Processing*. Guwahati, Assam, India: Association for Computing Machinery; 2016:Article 65.
48. Prakosa A, Southworth MK, Avari Silva JN, Silva JR, Trayanova NA. Impact of augmented-reality improvement in ablation catheter navigation as assessed by virtual-heart simulations of ventricular tachycardia ablation. *Comput Biol Med*. 2021;133:104366. [CrossRef]
49. Li R, Yang T, Si W, et al. Augmented reality guided respiratory liver tumors punctures: a preliminary feasibility study. In: *SIGGRAPH Asia 2019 Technical Briefs*. Brisbane, QLD, Australia: Association for Computing Machinery; 2019:114-117.
50. Kamath AA, Friedman DD, Akbari SHA, et al. Glioblastoma treated with magnetic resonance imaging-guided laser interstitial thermal therapy: safety, efficacy, and outcomes. *Neurosurgery*. 2019;84(4):836-843. [CrossRef]
51. Pech M, Wieners G, Freund T, et al. MR-guided interstitial laser thermotherapy of colorectal liver metastases: efficiency, safety and patient survival. *Eur J Med Res*. 2007;12(4):161-168.
52. Rennert RC, Khan U, Bartek J, Jr, et al. Laser ablation of abnormal neurological tissue using robotic neuroblate system (LAANTERN): procedural safety and hospitalization. *Neurosurgery*. 2020;86(4):538-547. [CrossRef]
53. Natarajan S, Raman S, Priester AM, et al. Focal laser ablation of prostate cancer: phase I clinical trial. *J Urol*. 2016;196(1):68-75. [CrossRef]
54. Oertel, MF, Stieglitz, LH, Bozinov, O. A stereotactic frame-based drill guide-aided setting for laser interstitial thermal therapy. *Acta Neurochir*. 2021;163:3447–3453. [CrossRef]
55. Bistaman INM, Idrus SZS, Rashid SA. The use of augmented reality technology for primary school education in Perlis, Malaysia. *J Phys Conf S*. 2018;1019:012064. [CrossRef]
56. Cheng R, Xu S, Bokinsky A, et al. GPU based multi-histogram volume navigation for virtual bronchoscopy. *Annu Int Conf IEEE Eng Med Biol Soc*. 2014;2014:3308-3312. [CrossRef]
57. Cancer Treatment Centres of America (CTCA). *Interventional Radiology. Secondary Interventional Radiology May 21, 2021*. 2021. Available at: https://www.cancercenter.com/treatment-options/interventional-oncology/interventional-radiology.