Magnetic Resonance Thermometry and Laser Interstitial Thermal Therapy for Brain Tumors

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KEYWORDS

• Thermometry • Laser interstitial thermal therapy • Brain tumors • Intraoperative imaging

KEY POINTS

- Recent technological advancements in intraoperative imaging are shaping the way for a new era in brain tumor surgery.
- Magnetic resonance thermometry has provided intraoperative real-time imaging feedback for safe and effective application of laser interstitial thermal therapy (LITT) in neuro-oncology.
- Thermal ablation has also established itself as a surgical option in epilepsy surgery and is currently used in spine oncology with promising results.

INTRODUCTION

LITT has emerged as a new treatment option for various conditions within the neurosurgery world, not only due to its minimal invasiveness but also because it has been shown safe and effective. In recent years, LITT has become a reality in neuro-oncology[1–10] and epilepsy surgery[11–14] and is emerging as an option in spine surgery[15–17] and chronic pain syndromes.[17–19]

Although introduced in 1983 by Bown,[20] who demonstrated focal tissue photocoagulation in an experimental brain tumor model using an Nd:YAG laser, the clinical application of LITT was limited due to the inability to monitor and control laser-induced thermal damage to the target volume in a real-time fashion. The groundbreaking technological advancement, which allowed the widespread application of LITT in neurosurgery, was the development of MRI thermometry.[21] MRI thermometry allows real-time image feedback of laser thermal energy delivery, making it possible to predict the thermal damage of a planned target in the brain.[21] This article describes the application of LITT with a focus in neuro-oncology.

PRINCIPLES AND RATIONALE OF LASER INTERSTITIAL THERMAL THERAPY

LITT exerts its biological effect through thermal damage.[1] Laser light photons are absorbed by neighboring tissue, which causes excitation and release of thermal energy that spreads to nearby structures by means of 2 phenomena, convection and conduction.[1,22–25] Two factors are determinant of the degree of heat penetration into surrounding tissue: the physical properties of the tissue itself and the characteristics of the laser energy itself.[26] In relation to the properties of the tissue, literature has shown that the amount of

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hemoglobin and water present in tissues are the main factors responsible for laser absorption.[27] Regarding the energy used to produce the laser beam, the greatest degree of tissue penetration, in the range of 10 mm, is achieved with laser radiation with wavelengths in the near-infrared part of the spectrum.[27]

LITT produces a sequence of biochemical events at the cellular level characterized by enzyme induction, denaturation of proteins, and breakdown of cellular membranes culminating with coagulation necrosis and blood vessel sclerosis.[27] The end result of surgically applied laser technology can be photocoagulation, photovaporization, or photosensitization.[28] LITT promotes photocoagulation, by providing a source of constant and continuous laser delivery to the target volume. Importantly, rapid increases in temperature should be avoided because they can result in tissue carbonization,[29] which prevents adequate laser absorption. In addition, overheating can cause tissue vaporization, which could lead to increased intracranial pressure.[30] When performing LITT, the aim is to precisely promote coagulation necrosis of the specific target without causing carbonization or vaporization of the treated area. Three zones of histologic changes around the laser probe have been described.[29] The first zone is the area closest to the tip of the probe and represents the area of greatest tissue damage due to the highest degree of energy absorption.[29] Coagulation necrosis occurs at temperatures in the range of 50°C to 100°C.[29] Carbonization and vaporization are usually seen at temperatures above 100°C. The volume of tissue in the second or intermediate zone also undergoes thermal injury. Cells located at the third and most marginal zone, although damaged by thermal energy, are still viable.[29] True coagulation necrosis is observed in the first 2 zones.[29] The 3 zones of thermal damage may be displayed by the computer software as the thermal-damage-threshold (TDT) lines, through data acquired by MRI thermometry. This feature allows surgeons to customize the ablation based on the target volume, which ideally should be included in the first 2 zones.

As discussed previously, LITT is also affected by the optical properties of the targeted tissue. Studies focusing the optical properties of native and coagulated human brain tissue revealed that the deepest area of thermal coagulation and highest laser penetration were found in the wavelength range between 1000 nm and 1100 nm, which is in the near-infrared part of the electromagnetic spectrum.[31] Furthermore, the depth of interstitial thermal damage and subsequent necrosis depends on the cooling conditions of the system, power density, and exposure time.[32,33] Within the near-infrared part of the spectrum, the laser interaction with white matter and gray matter is different. Although gray matter shows a high level of laser absorption, white matter displays the lowest. The degree of laser penetration also varies depending on the tumor type. Research shows that tumors like glioblastomas (GBMs) and meningiomas exhibited the highest degree of laser absorption, whereas low-grade glioma displayed optical properties similar to gray matter.[34] Optimal laser ablation is achieved when a sharp border of thermal injury is observed at the brain-tumor interface characterizing a selective procedure with preservation of the normal brain tissue surrounding the tumor. Also, the extent of volume and surface area overlap between TDT lines and corticospinal tracts has been shown to correlate with postoperative motor deficits and needs to be considered during LITT procedure.[6]

The game changer allowing the use of LITT for brain tumors was the capability to visualize real-time temperature changes in deep regions of the body,[35,36] which was granted by MRI thermometry. Its principle relies on the temperature-dependent water proton resonance frequency (PRF). PRF image mapping is based on the premise that protons are displaced more efficiently within the magnetic field in the form of free water molecule (H_2O) than in the form of hydrogen-bonded water molecules. Thus, as thermal energy is delivered during LITT and temperature increases, the number of hydrogen bonds decrease, resulting in an increased number of free H_2O molecules and a lower PRF, which is then visualized with MRI thermometry coupled with advanced computer software in real-time fashion.[37,38]

TECHNICAL NUANCES AND COMMERCIALLY AVAILABLE SYSTEMS

Lasers and Probes Used for Laser Interstitial Thermal Therapy

The 2 main types of lasers used for LITT are the continuous-wave Nd:YAG and diode lasers. Wavelengths in commercial systems range from 980 nm to 1064 nm and operate at a wide range of powers.[1,29,30] Longer wavelength achieve higher tissue penetration especially in soft tissues with high blood whereas lower wavelengths are capable of producing lesions faster but typically with less penetration.[2]