Preliminary experience with a transcranial magnetic resonance–guided focused ultrasound surgery system integrated with a 1.5-T MRI unit in a series of patients with essential tremor and Parkinson’s disease

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OBJECTIVE
Transcranial magnetic resonance–guided focused ultrasound surgery (tcMRgFUS) is one of the emerging noninvasive technologies for the treatment of neurological disorders such as essential tremor (ET), idiopathic asymmetrical tremor-dominant Parkinson’s disease (PD), and neuropathic pain. In this clinical series the authors present the preliminary results achieved with the world’s first tcMRgFUS system integrated with a 1.5-T MRI unit.

METHODS
The authors describe the results of tcMRgFUS in a sample of patients with ET and with PD who underwent the procedure during the period from January 2015 to September 2017. A monolateral ventralis intermedius nucleus (VIM) thalamic ablation was performed in both ET and PD patients. In all the tcMRgFUS treatments, a 1.5-T MRI scanner was used for both planning and monitoring the procedure.

RESULTS
During the study period, a total of 26 patients underwent tcMRgFUS thalamic ablation for different movement disorders. Among these patients, 18 were diagnosed with ET and 4 were affected by PD. All patients with PD were treated using tcMRgFUS thalamic ablation and all completed the procedure. Among the 18 patients with ET, 13 successfully underwent tcMRgFUS, 4 aborted the procedure during ultrasound delivery, and 1 did not undergo the tcMRgFUS procedure after stereotactic frame placement. Two patients with ET were not included in the results because of the short follow-up duration at the time of this study. A monolateral VIM thalamic ablation in both ET and PD patients was performed. All the enrolled patients were evaluated before the treatment and 2 days after, with a clinical control of the treatment effectiveness using the graphic items of the Fahn-Tolosa-Marin tremor rating scale. A global reevaluation was performed 3 months (17/22 patients) and 6 months (11/22 patients) after the treatment; the reevaluation consisted of clinical questionnaires, neurological tests, and video recordings of the tests. All the ET and PD treated patients who completed the procedure showed an immediate amelioration of tremor severity, with no intra- or posttreatment severe permanent side effects.

CONCLUSIONS
Although this study reports on a small number of patients with a short follow-up duration, the tcMRgFUS procedure using a 1.5-T MRI unit resulted in a safe and effective treatment option for motor symptoms in...
Ablation method, which uses high-intensity focused ultrasound (MRgFUS) has emerged as a noninvasive thermal setting, magnetic resonance–guided focused ultrasound and real-time thermal mapping. Thanks to this novel sound (HI-FU) energy and MRI for anatomical imaging and functional and movement disorders: 20 patients suffered from ET, 4 patients suffered from PD, 1 patient suffered from Tourette’s disease (PD), essential tremor (ET), and neuropathic pain. Currently, this procedure is being used for new clinical and experimental scenarios. In functional neurosurgery, transcranial MRgFUS (tcMRgFUS) is definitely emerging as a noninvasive, nonprosthetic, guided, and repeatable technique for treating mostly idiopathic tremor–dominant Parkinson’s disease (PD), essential tremor (ET), and neuropathic pain.

ET and PD are neurological disorders with a high prevalence. The history of their pathological progression leads to drug resistance and to the decline of quality of life. In this clinical series we aim to present the results obtained by treating tremor in patients suffering from ET and PD with the world’s first tcMRgFUS system integrated with a 1.5-T MRI unit.

Methods

Patients and Study Criteria

From January 2015 to September 2017 at the University Hospital “Paolo Giaccone” of Palermo, Italy, 26 patients underwent tcMRgFUS thalamic ablation for different functional and movement disorders: 20 patients suffered from ET, 4 patients suffered from PD, 1 patient suffered from neuropathic pain, and 1 patient suffered from intentional tremor secondary to multiple sclerosis (MS). Among these 26 patients, only 23 were enrolled in this study: 18 with ET, 4 with PD, and the 1 patient with MS (Table 1). The patient with MS was not treated because of a sudden laryngospasm while she was lying on the MRI machine, before the sonication was performed. The 4 patients with PD (4 men, mean age 68 ± 4.74 years) were all treated by tcMRgFUS thalamic ablation and completed the procedure. Among the 18 patients with ET (13 men, 5 women, mean age 65 ± 13.02 years), 13 successfully underwent tcMRgFUS (10 men, 3 women, mean age 65.22 ± 11.87 years), 4 aborted the procedure during ultrasound delivery, and 1 did not undergo tcMRgFUS after stereotactic frame placement. Two patients with ET were not considered for treatment because of a short follow-up duration at the time of manuscript submission. The patients who completed the procedure were treated by monolateral tcMRgFUS ventralis intermedium nucleus (VIM) thalamic ablation both in cases of ET and in cases of PD.

Eligibility criteria were age between 18 and 80 years, patient ability to give informed consent and undergo clinical evaluations, the possibility of performing CT and MRI, and a proper skull density ratio. In both ET and PD patients, tremor had to be confirmed by a movement disorder–skilled neurologist, be resistant to a stable dose of medications, and cause substantial disability in daily life. The interruption of pharmacological therapy before the treatment, because of its inefficiency, was not considered an exclusion criterion. Every patient who did not meet such eligibility criteria, suffered from psychiatric illness, presented a risk of bleeding, had neurological and cardiovascular comorbidities, had dermatological illness on the scalp, or had a standard contraindication to CT/MRI was excluded from the treatment. Demographic data are shown in Table 1.

Outcome Evaluation

All enrolled patients were evaluated before the treatment (baseline). The follow-up evaluations were performed 2 days and then 3 (17/22 patients) and 6 months (11/22 patients) after the treatment. These evaluations consisted of clinical questionnaires, neurological tests, and video recordings of the tests.

Tremor severity was evaluated by the neurosurgeons using the Fahn-Tolosa-Marin (FTM) tremor rating scale in the patients with ET, and the third section of the Unified Parkinson’s Disease Rating Scale (UPDRS) in the 4 patients with PD.

For the purpose of this study, only the scores obtained from patients who completed the tcMRgFUS procedure were considered and analyzed. For each patient with ET, the global FTM score (range 0–144) was assessed before treatment and at the 3- and 6-month follow-up evaluations; the second section of the FTM scale (graphic ability, range 0–16) for the contralateral hand was also evaluated on the 2nd day after the treatment to assess the immediate improvement in graphic abilities.

All the patients with ET enrolled in this series were...
also evaluated with the Quality of Life in Essential Tremor (QUEST) questionnaire at baseline and at 3- and 6-month follow-up evaluations to assess their quality of life (range 0%–100%, in which 100% is the greatest perceived disability and the worst quality of life).

For each patient with PD, the third section of the UPDRS was assessed before the treatment (baseline) and at 3 months. No evaluation at 6 months has been performed yet.

Patients underwent neurological assessment before and after each treatment. Moreover, after each sonication, the tremor and its amelioration were assessed by a clinical evaluation and drawing tests.

Brain screening and follow-up MRI were performed with a Signa HDxt 1.5-T unit (GE Medical Systems) using an 8-channel phased-array head coil. The MRI conventional protocol used for screenings and follow-up evaluations included 2D axial fast spin echo (FSE) T1- and T2-weighted pulse sequences, sagittal T2-weighted 3D CUBE FLAIR with fat saturation, sagittal 3D T1-weighted fast spoiled gradient echo (FSPGR), and axial 3D susceptibility-weighted angiography (SWAN; 3-mm thickness). The tcMRgFUS specific planning protocol included sagittal, coronal, and axial high-resolution (2-mm-thick/no gap) T2-weighted fast recalled FSE (FRFSE). The same planning sequences were used for live MRI during the treatments, using a dedicated 2-channel head coil. CT brain scans were acquired using a 16-channel multidetector CT unit (BrightSpeed, GE Medical Systems) with the following parameters: tube voltage 120 kV, tube current 220 mA, pure axial plane (0° gantry tilting), sequential acquisition, 1.25-mm slice thickness, and bone kernel.

### tcMRgFUS Thalamotomy Procedure

This tcMRgFUS system (ExAblate 4000, InSightec Ltd.) consists of a hemispheric 1024-element phased-array transducer operating at 650 kHz, similar to those used with 3.0-T MRI units. 7

Before the procedure, the patient’s scalp was shaved and fixed with the stereotactic frame (Fig. 1A), and a sealant membrane with the embedded dedicated coil was positioned on the head of the patient (Fig. 1B). Once the frame was locked to the helmet, the helmet itself was filled with degassed circulating cooled water for an optimal coupling and to avoid any heat damage to the skin and to the skull. During the treatment, the patient and both the monitoring and the operating physicians had access to an emergency stop sonication button. Patient vital signs were constantly monitored during each procedure.

Target position was calculated on MR images by canonical stereotaxic coordinates: 75% of the intercommissural line (anterior commissure–posterior commissure

### TABLE 1. Demographic data of enrolled patients

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Disorder</th>
<th>Disease Duration (yrs)</th>
<th>tcMRgFUS at Treatment</th>
<th>Therapy at Treatment</th>
<th>Treated Hand</th>
<th>FU (mos)</th>
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<tbody>
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<td>1</td>
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<td>ET</td>
<td>45</td>
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<td>6</td>
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<tr>
<td>3</td>
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<td>Rt</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
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<td>25</td>
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<td>Rt</td>
<td>6</td>
</tr>
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<td>6</td>
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<td>Rt</td>
<td>3</td>
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<tr>
<td>10</td>
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<td>ET</td>
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<td>Bromazepam, primidone</td>
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<td>Completed</td>
<td>Propranolol</td>
<td>Rt</td>
<td>6</td>
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<td>ET</td>
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<td>Completed</td>
<td>Primidone</td>
<td>Rt</td>
<td>6</td>
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<td>Aborted (severe HA)</td>
<td>Delorazepam</td>
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<td>Aborted</td>
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<tr>
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<td>Aborted</td>
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<tr>
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<td>Rt</td>
<td>Aborted</td>
</tr>
<tr>
<td>17</td>
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<td>ET</td>
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<td>Aborted (low temp)</td>
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<td>Rt</td>
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<td>18</td>
<td>72, F</td>
<td>ET</td>
<td>22</td>
<td>NP (TIA)</td>
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<td>NP</td>
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<td>MS</td>
<td>5</td>
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<td>3</td>
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<td>21</td>
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<tr>
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<td>Levodopa, carbidopa, pramipexole, amitriptyline</td>
<td>Rt</td>
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</table>

FU = follow-up; HA = headache; NP = not performed; temp = temperature; TIA = transient ischemic attack.
The right hand was the tremor-dominant hand in all patients.
line), 12–14 mm laterally from the median plane, and 0–2 mm caudocranially from the intercommissural plane. For each patient, the treatment was planned by registering the CT and MRI images, marking as “no pass” regions any calcifications and other critical regions that could affect the HI-FU path. The number of transducer elements that had to be employed (should not be < 700) and the actual head surface (should not be < 250 cm²) available for the energy required to be delivered were thus calculated. Fiducial markers were placed on live MR images to enable automatic movement detection.

Before starting the procedure, a tracking scan was run to verify and register the transducer home position, and the central MRI frequency was verified. The transducer’s focal point and the MRI system alignment in all 3 axes were verified before the actual treatment by performing short (10-second) low-energy sonifications (≤ 250 W). The HI-FU beam power was then gradually increased to

**FIG. 1.** Images showing patient preparation for tcMRgFUS.  **A:** Stereotactic frame positioning.  **B:** Patient sitting on the dedicated MRI table with the stereotactic frame fixed and the silicon sealant membrane already positioned; 1 of the 2 rings of the dedicated coil is clearly visible on the left side of the patient’s head.

**FIG. 2.** ExAblate Neuro workstation and treatment plan.
achieve temperatures in the range of 50°–54°C that will result in a transient clinical effect. Once the optimal target was confirmed, and no side effects were reported by the patient, a further increase in the HI-FU beam power was used to achieve higher temperatures (≥ 55°C) to obtain a permanent lesioning of the targeted volume (Fig. 2).

At the end of each cluster of lesioning sonications, high-resolution T2-weighted sequences were acquired by the dedicated 2-channel head coil to visualize the resulting thalamic lesion. Neither steroid treatment nor osmotic drugs were administered after the treatments.

Results

For all 13 patients with ET and 4 patients with PD who completed the tcMRgFUS procedure, the thalamic VIM was chosen as the target. In 17 patients the left VIM was ablated, which was contralateral to the dominant hand, in both ET and PD cases. The right VIM was ablated in only 1 patient, which was contralateral from the onset of the tremor, to effectively treat an axial tremor.

Tremor

All the ET and PD treated patients who completed the procedure did show a substantial and immediate improvement in graphical and neurological tests. A subjective improvement of axial and voice tremor was also reported by the patients with ET who suffered from this symptomatology.

At baseline, the FTM global score for all the treated patients with ET showed a mean value of 40.2 ± 11.8 (range 15–63) and the second section of the FTM reported a mean hand tremor score of 6.4 ± 2.97 (range 3–13). Two days after the treatment, a meaningful 66.4% reduction of tremor was reported by the second section of the FTM, with a mean value of 2.15 ± 0.86 (range 1–3). No improvement was shown in the ipsilateral side of the body to the treated thalamus.

All the patients underwent the 3-month follow-up evaluation, while the 6-month evaluation was performed only in 11 patients with ET. At the 3-month follow-up, a meaningful reduction of tremor was reported by the second section of the FTM, with a mean value of 2.15 ± 0.86 (range 1–3). No improvement was shown in the ipsilateral side of the body to the treated thalamus.

All the patients who underwent the 3-month follow-up evaluation did show a substantial and immediate improvement in graphical and neurological tests. A subjective improvement of axial and voice tremor was also reported by the patients with ET who suffered from this symptomatology.

TABLE 2. Follow-up overview of patients with ET who underwent successful tcMRgFUS

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Hand Score (graphic ability)</th>
<th>Global FTM Score</th>
<th>QUEST Score</th>
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<td></td>
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<td>1</td>
<td>3 1 2 6</td>
<td>44 22 29</td>
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<td>26.85 9.61 9.8</td>
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<td>6 2 2 2</td>
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<tr>
<td>Mean</td>
<td>6.4 2.2 2.1 2.2</td>
<td>40.2 17.3 17.7</td>
<td>35.09 17.09 18.44</td>
</tr>
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</table>

TABLE 3. Follow-up overview of patients with PD who underwent successful tcMRgFUS

<table>
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<tr>
<th>Case No.</th>
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<td>20 11</td>
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<tr>
<td>21</td>
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<tr>
<td>23</td>
<td>55 26</td>
</tr>
<tr>
<td>Mean</td>
<td>36.5 17.5</td>
</tr>
</tbody>
</table>

All patients are currently in follow-up at the 6-month interval.

* Third section of the UPDRS.
Adverse Events

Among the 18 patients with ET enrolled in this study, 5 did not complete the tcMRgFUS procedure. In 4 of them the procedure was aborted because of a sudden and intense remitting headache related to the HI-FU delivery. In the last patient, the procedure was aborted after several sonications because of the failure in reaching a sufficient temperature to perform ultrasonic thalamic ablation, due to the patient’s skull thickness and density ratio.12 The procedure was voided in a single enrolled patient, who did not undergo any sonication because of a severe blood pressure increase, which led to a transient ischemic attack related to a stress response of the patient to the stereotactic frame placement. The patient was medically treated and monitored in a semi-intensive care unit until the symptoms faded in a few hours.

Among the 13 ET and 4 PD patients enrolled and treated, 2 showed temporary paresthesias to the contralateral hand. One patient showed temporary weakness in grip to the treated hand, which faded in about a week. Four patients showed gait disturbance after the thalamotomy: in 2 of them ataxia completely faded within the time of discharge; in another patient ataxia partially improved within the time of discharge and had completely disappeared at 3 months’ follow-up; in the last patient, ataxia was noticed during the entire 6 months of follow-up. Two patients reported a subjective loss of balance; in 1 of these patients it lasted for the entire follow-up period.

In a self-assessment test performed on the 2nd day after the treatment, no patient complained about any moderate or severe disability or any other generic symptoms. Most of the patients reported tiredness, often referring to the hospitalization itself. In only a few patients a slight weakness on the contralateral side of the body was reported.

Regarding the stereotactic frame placement, 3 patients showed temporary headache after the frame removal: 1 patient showed a temporary scalp numbness, which faded in about 24 hours, and 1 patient reported a skin wound due to the placement of the pin of the frame. In a single patient, a minor displacement of the stereotactic frame was reported during the last stages of the treatment, which was corrected by electronic steering only.

During HI-FU delivery, 4 patients complained of dizziness and paroxysmal vertigo. One patient reported a feeling of water flushing around the head even after the frame removal, and a single patient experienced a subjective postural instability leaving the MRI table. No major adverse event was noted.

Neuroradiological Evaluation

T2-weighted MRI sequences acquired at the end of each treatment showed the resulting thalamotomy as a hyperintense round-shaped lesion with a variable amount of perilesional vasogenic edema. Every treated patient underwent brain MRI 48 hours after the treatment with the reported protocol (Fig. 3). At this time, on T2-weighted pulse sequences, VIM lesions showed the typical imaging findings with 3 typical concentric zones:56 a central dark spot (not always clearly appreciable) with a strongly hyperintense peripheral zone demarcated by a hypointense rim and a slightly hyperintense zone of perilesional vasogenic edema (Fig. 3A). The lesion itself showed a true restriction of water molecule movements on apparent diffusion coefficient maps (Fig. 3D). Susceptibility-weighted imaging showed blood products within the core of the lesions (Figs.
3B and 4). At the 48-hour follow-up MRI, all the lesions had almost doubled in size and the amount of perilesional vasogenic edema had increased. On subsequent follow-up images lesion size shrank, until they almost disappeared on T2-weighted pulse sequences after 6–9 months (Fig. 4). In some cases, small spots of blood-brain barrier (BBB) leaks were still appreciable at the 48-hour MRI follow-up (Fig. 3F), but never on subsequent MRI follow-ups. Susceptibility-weighted imaging revealed the presence of hypointense intralesional blood products (hemosiderin) on all follow-up MRI examinations despite the normalization of other MRI findings on conventional pulse sequences (Fig. 4).

Discussion

In this clinical series in which 13 ET and 4 hyperkinetic PD patients were evaluated, thalamic VIM ablation was performed by tcMRgFUS. The data obtained did show an amelioration of contralateral tremor, as demonstrated by the results from graphical tests and the FTM. Moreover, a significant quality of life improvement was shown, as assessed by the QUEST questionnaire.

To the best of our knowledge, this is the first series of patients treated with a tcMRgFUS system integrated with a 1.5-T unit. In this method, tcMRgFUS thalamotomy emerges as a safe, effective, and noninvasive technique in treating specific movement disorders, even using the most common and affordable 1.5-T MRI machines. In addition, tcMRgFUS thalamotomy allows a monolateral treatment, compared with traditional deep brain stimulation, but with shorter durations and fewer surgical risks.

The first clinical study of tcMRgFUS feasibility began in 2008 for the treatment of drug-resistant thalamic neuropathic pain.32 Further studies about the treatment of behavioral disorders have already been published.38

Regarding movement disorder treatment, the study of Elias et al. performed in 2013 demonstrated the effective thalamic VIM ablation through tcMRgFUS in a population of 15 drug-resistant patients with ET. In that series, a significant improvement of tremor and quality of life was obtained after 1 year of follow-up. The randomized trial that followed that series in 2016 confirmed the effectiveness of tcMRgFUS in 67 patients with ET compared with the sham procedure. In this trial, an amelioration of hand tremor from 18.1 to 9.6 points was found. In 2013, a second preliminary study about ET treatment through tcMRgFUS confirmed the effectiveness of this technique.41 In the same year, positive results were obtained from the tcMRgFUS treatment of 8 patients with PD, with an improvement of 57.1% at 3 months in the UPDRS evaluation; these results were confirmed in 2014 by a significant UPDRS improvement.

In all the reported series, tcMRgFUS treatments were performed using 3-T MRI machines (Table 4). These units guarantee a greater spatial and contrast resolution but do not guarantee the same safety profile as 1.5-T MRI machines.33 Moreover, compared with 1.5-T magnets, 3-T magnets also suffer from higher susceptibility and dielectric artifacts that could severely influence imaging quality during tcMRgFUS treatments. Our preliminary results demonstrated the safety and the diagnostic and therapeutic effectiveness of a 1.5-T MRI machine for tcMRgFUS treatments.22,29 Regarding effectiveness, no difficulty or error in targeting was encountered and the targeting accuracy was confirmed by the clinical results. Moreover, the feasibility and effectiveness of tcMRgFUS performed with an affordable 1.5-T unit establishes the path to wider use of this emerging technique around the world, because 1.5-T MRI machines are widely installed worldwide and require lower purchase, installation, and maintenance costs.

For a long time, movement disorders and neuropathic pain have been treated with radiofrequency ablation, deep brain stimulation, or stereotactic radiosurgery. Unfortunately, these techniques are burdened by a high rate of ad-
verse events and surgical risks, with possible permanent neurological dysfunctions.\textsuperscript{10,17} Thanks to its noninvasiveness, tcMRgFUS avoids the risk of infection, lowers the risk of bleeding, and reduces adverse events and damage to the tissues surrounding the target. Also, tcMRgFUS allows clinical outcomes similar to those of radiofrequency ablation thalamotomy or deep brain stimulation,\textsuperscript{40,53} and it also permits one to obtain an immediate and verifiable lesion.\textsuperscript{11} It does not use ionizing radiation and it is a noninvasive technique; moreover, patient feedback allows the physician to optimize the target before a permanent lesion is made, because the clinical effect can be evaluated immediately during each sonication. Furthermore, the use of MRI as a guidance for the HI-FU beam allows a precise real-time location of the target volume, the establishment of precise safety margins, and a real-time temperature control.\textsuperscript{32} Lastly, it may be feasible to more easily consider re-treatment as an option in those cases in which tremor may return.

The profile of adverse events related to tcMRgFUS treatment appears to be similar to the profile of radiofrequency ablation thalamotomy, mainly due to wrong positioning or larger target volume.\textsuperscript{41} However, these risks are limited in tcMRgFUS treatment because it is a noninvasive technique that does not harm skull or brain parenchyma through probe insertion or because of uncontrollable lesion development. Interestingly, a progressive decrease in lesion volume has been shown in the long term after the tcMRgFUS procedure. In contrast, radiofrequency ablation lesions are less spatially controllable, and the Gamma Knife radiosurgical treatment creates lesions that may keep growing over time, with the possible occurrence of progressive neurological deficits.\textsuperscript{29}

**Future Perspectives in tcMRgFUS**

The feasibility of bilateral tcMRgFUS thalamotomy remains a matter of debate because of the high risk of adverse events in cases of permanent lesioning, in particular ataxia and speech disturbances.\textsuperscript{4,54} Despite this, promising results were obtained by Gallay and colleagues with bilateral cerebellothalamic tractotomy through tcMRgFUS in a series of 18 patients with ET.\textsuperscript{23} Gallay et al.’s study envisages the feasibility of bilateral lesioning without permanent side effects, even if this has not yet been replicated.\textsuperscript{50}

Several controlling technologies\textsuperscript{5} and applicable fields are now arising concerning new therapeutic perspectives of tcMRgFUS, such as neurooncological treatment,\textsuperscript{3,14,43} control of BBB permeability,\textsuperscript{9,44,45} controlled drug diffusion\textsuperscript{34,37} and antiblastic therapy across the BBB,\textsuperscript{2,19,35,43,55} subcortical drug-resistant epilepsy, obstructive hydrocephalus and drug-resistant psychiatric disorders,\textsuperscript{46} intracranial thrombosis through sonothrombolysis,\textsuperscript{25} and trigeminal neuralgia.\textsuperscript{47}

Despite the obtained results, this clinical series suffers from some limitations. Both patients and physicians were aware of the treatment performed in this study; the patient sample is small, and the follow-up duration is ongoing. Moreover, the present study lacks a control group, and therefore it has not been possible to evaluate the effectiveness of tcMRgFUS thalamotomy compared with the other stereotactic procedures that have been performed for a long time. Despite these limitations, every patient showed a significant amelioration of tremor in the treated hand and of the motor function, as shown by results from the clinical tests conducted after treatment. In this way, tcMRgFUS is confirmed as a reliable choice in the treatment of motor disorders, with a high profile of safety and effectiveness, even using a 1.5-T MRI unit.

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