JOURNAL OF NEUROSURGERY:
Case Lessons

J Neurosurg Case Lessons 4(22): CASE22259, 2022
DOI: 10.3171/CASE22259

Complete resolution of chronic cluster headache following central lateral thalamotomy using incisionless MRI-guided focused ultrasound with 6 years of follow-up: illustrative case

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BACKGROUND The authors reported the case of a 66-year-old male patient with a 14-year history of right-sided severe episodic and therapy-resistant cluster headache (CH) who underwent bilateral central lateral thalamotomy (CLT) using incisionless transcranial magnetic resonance imaging–guided focused ultrasound (MRgFUS).

OBSERVATIONS The patient experienced a single cluster headache attack 5 weeks after the procedure. There were no more pain attacks over the next 6 years of follow-up.

LESSONS This treatment success may indicate a common pathophysiology for CH and neurogenic (neuropathic) pain, which has been treated with CLT for more than 30 years. Further experience is needed to assess the reproducibility of this case.

https://thejns.org/doi/abs/10.3171/CASE22259

KEYWORDS cluster headache; neurogenic pain; neuropathic pain; stereotactic functional neurosurgery; minimally invasive; incisionless; MRI-guided focused ultrasound; central lateral thalamotomy

Cluster headache (CH) is a form of trigeminal autonomic cephalalgia[1] characterized by severe, strictly unilateral pain with a slight right-sided predominance[2,3] occurring from once every other day to several times a day. Locations of the pain can be orbital, supraorbital, temporal, or any combination of these sites. They can last up to 3 hours, and the pain is associated with prominent parasympathetic autonomic features. Prevalence of CH is approximately 0.1% in the general population and favors men over women at a ratio of 3:1.[4]

CH can be highly disabling and is known to be increasingly difficult to control with medication as it progresses over time.[5] Rates of depression with suicidal thoughts were found to be as high as 55% in two CH patient cohorts.[3,6] Some genetic constellations,[7] tobacco exposition,[8] and an unhealthy lifestyle[9] seem to be predisposing factors.

Drug treatments for CH include long-term prophylactic as well as acute abortive measures.[10,11] For the latter, sumatriptan and oxygen are the most effective treatments, with a central effect on vasodilatation. Surgical interventions for therapy-refractory CH include deep brain stimulation (DBS) of the posteroinferior hypothalamic area,[12] occipital nerve stimulation,[13] stimulation of the sphenopalatine ganglion,[14] vidian neurectomy,[15] and invasive and noninvasive vagus nerve stimulation.[16]

Various peripheral and central nervous structures have been proposed to harbor mechanisms at the source of CH attacks:[17] (1) the trigeminal nucleus and ganglion, (2) the parasympathetic system (superior salivatory nucleus and sphenopalatine ganglion), (3) the sympathetic system (intermediolateral nucleus and superior cervical ganglion), and (4) the hypothalamus.[18,19] In addition, the pain-related brainstem nuclei (particularly the periaqueductal gray) and the whole thalamocortical (TC) pain network have to be considered. Involvement of the parasympathetic system is evidenced

ABBREVIATIONS CH = cluster headache; CLp = central lateral nucleus; CLT = central lateral thalamotomy; DBS = deep brain stimulation; EEG = electroencephalography; LTS = low-threshold calcium spike; MR = magnetic resonance; MRgFUS = MRI–guided focused ultrasound; MRI = MR imaging; TC = thalamocortical; TCD = thalamocortical dysrhythmia.

INCLUDE WHEN CITING Published November 28, 2022; DOI: 10.3171/CASE22259.
SUBMITTED June 23, 2022. **ACCEPTED** August 29, 2022.

by the appearance of conjunctival injection, lacrimation, and rhinorrhea as well as cranial and extracranial vasodilatation. Parasympathetic manifestations were observed in more than 90% of patients with CH.[20,21]

Despite large amounts of data collected on all these structures, the pathophysiological origin of CH remains elusive.

Neurophysiological studies at the cellular level (microelectrode single unit recordings and local field potentials)[22] as well as electro- and magnetoencephalographic recordings provide converging evidence for a TC dysregulation at the source of chronic neurogenic (neuropathic) pain of both peripheral and central origin.[23,24] This dysregulation is characterized by an overactivity of the TC network driven by a physiological thalamic switch toward an increase of low electroencephalography (EEG) frequencies and final cortical overactivity in the low and high frequencies (see discussion for details). The central lateral thalamotomy (CLT) was developed based on these data and on those collected in the 1950s and 1960s[25] in the context of medial thalamic interventions.

We present a single case of therapy-resistant CH treated with bilateral CLT performed in one session using the incisionless technique of magnetic resonance imaging–guided focused ultrasound (MRgFUS), with a follow-up of 6 years. This treatment approach was based on a possible common or similar pathophysiology for both neurogenic pain and CH pain syndromes.

The intensity of the pain syndrome, its therapy resistance, and the high suffering level experienced by our patient led us to consider MRgFUS CLT, a routine intervention in our hands in the context of chronic neurogenic pain, out of compassion. The patient refused any type of device implantation or neurotomy. Following a detailed explanation of the available data, the patient agreed to intervention.

Illustrative Case

History and Examination

The patient presented at the age of 60 with a 14-year history of increasing episodic cluster headaches. There were no known preexisting medical conditions or injuries, except for an episode of reactive depression in a context of work overload. He quit smoking at the age 50 (45 pack-years).

Symptoms started as an episodic tension-type headache. Over the first 2 years, it developed into attacks of severe, strictly right-sided headache attacks.

The description of the CH episode was the following: tension in the face and head on the right. Slow progressive increase of pain during the following 30 minutes up to 100/100 (on the visual analog pain scale) lasting 10 to 15 minutes. Thereafter, progressive reduction of pain intensity occurred over 20 to 30 minutes. Pain episodes ranged between 20 and 45 minutes, up to a maximum of 90 minutes. Pain was localized in the right eye, infraorbitally and laterally to the nose on the second trigeminal branch as well as preauricular and temporal on the third trigeminal branch, sometimes with radiation down to the chin. During the pain episodes, the face was strongly distorted to the right. The frequency of pain episodes was 0 to 7 times per day. Two-thirds of the pain attacks occurred during sleep. Over the years, the pain-free intervals shortened from 7 months to less than 3 months.

The pain qualities were described as tension and sometimes crushing (top of the head), pins and needles, burning, pulling/tearing (eye) and throbbing/hammering. The pain was felt deeply and was accompanied by a strong reduction of sensory perception in the infraorbital, nasal, and lateroorbital areas.

During the pain episodes, there was always phono- and photophobia as well as a strong hypersensitivity to physical contact on the whole body, increased salivation, tears and nasal flow strictly on the right, accompanied by obstruction of the right nostril and narrowing of the right palpebral fissure. The pain intensity was very high, inducing the patient to scream and get desperately agitated.

Pain-increasing factors were local or environmental heat as well as bad air and strong smells, red wine, stress, and anger. Slight pain reduction could be achieved by pressure on the right side of the face and local application of cold as well as relaxing walks in nature.

The patient was asked to assess some aspects of his general condition. A scale from 0 to 4 was used, with 0 indicating no problems and 4 indicating the maximum. Suffering due to pain was assessed between 2 and 3 out of 4 as well as a reduction in quality of life. The patient indicated a tendency to depression at 1 to 2 out of 4, anxiety at 1 out of 4, frustration at 1 to 2 out of 4. Social withdrawal due to pain was estimated at 2 to 3 out of 4, and the reduction in daily and leisure activities 2 to 3 out of 4.

The clinical findings during the painless intervals were a slight reactive myosis on the right with slight reduction of the palpebral fissure, a symmetrical corneal reflex, and a mild hypoesthesia and hypoalgesia on the right-sided first trigeminal branch, and on the second branch on the cheek to the lateral part of the orbit. Blood pressure was 110–120/70–80 mm Hg.

MRI of the Brain Was Normal

The following therapies were tried. Sumatriptan subcutaneous injection 6 mg provided a partial abortive pain relief (40% pain reduction after 15 minutes). Such injections were performed 4 to 7 times/day or 20 to 30 times per week. Oxygen therapy 8 L/min was unsuccessful. Nonsteroidal antiinflammatory drugs (NSAIDs) (e.g., Indometacin 75 mg) had no pain-relieving effect. Various preventive medications were tried. Cafergot (ergotamine tartrate 1 mg and 100 mg caffeine) did not reduce the numbers of attacks but seemed to potentiate the effect of the sumatriptan injections, with the patient reporting pain relief up to 60%. Isoptin up to 3 $\times$ 240 mg/day during 5 years provoked asthenia and was of no certain benefit. Topamax was administered up to 150 mg. It had no effect, and higher dosages induced anorexia (weight loss of 12 kg). Lithium and steroids had no effect on the pain attacks and were badly tolerated, especially at the psychoemotional level. Melatonin, valproic acid, Lamotrigin, and Baclofen had no effect. Monoclonal calcitonin gene-related peptide monoclonal antibodies[26] were not available at the time.

Electrophysiological Findings

The spectral analysis of the patient's EEG is shown in Fig. 1. The preoperative quantitative EEG examination revealed cortical overactivity in the delta, theta, alpha, and beta 1 frequency domains. Low-resolution electromagnetic tomography analysis[27] showed that this cortical overactivity was covering entire brain hemispheres and was maximal on both sides of the frontotemporoinsular, frontopolar, orbitofrontal, frontal interhemispheric, and frontal dorsolateral regions as well as cingulate regions. The entire cingulate area was affected, from subgenual to retrosplenial areas.

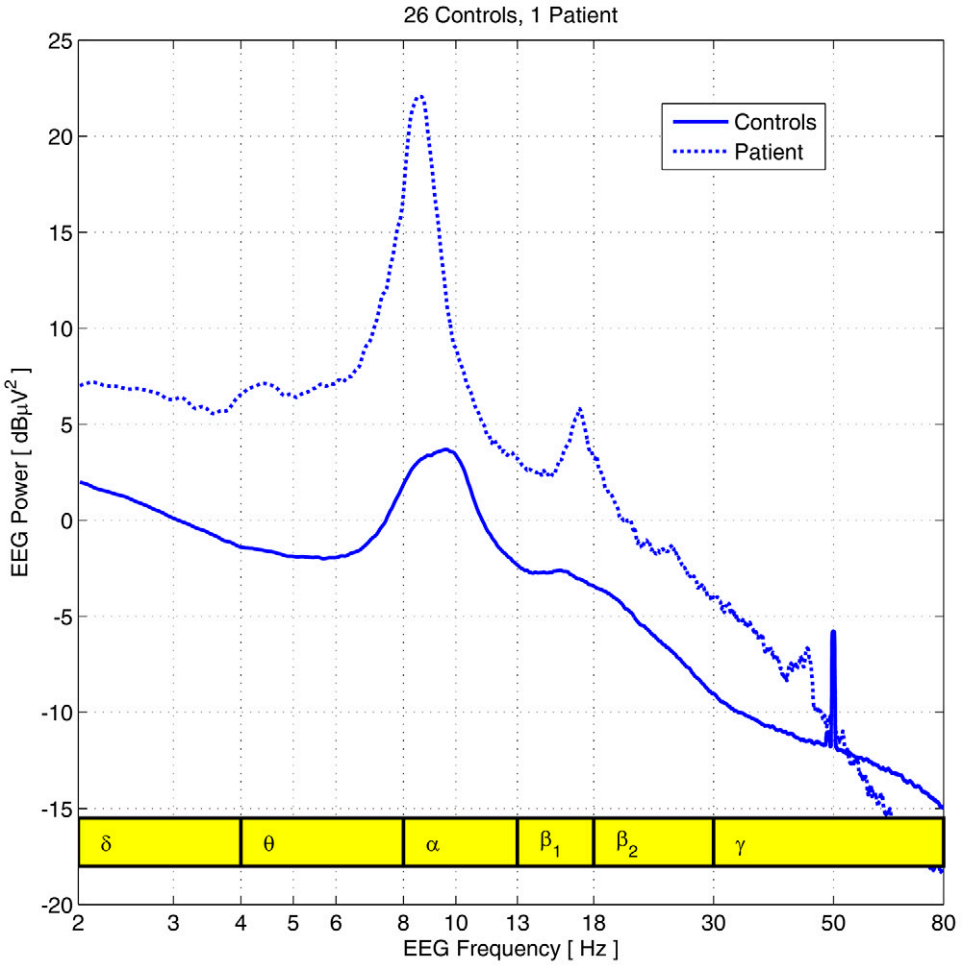

FIG. 1. Mean power spectrum over 61 electrodes in the CH patient (Patient). The *solid line* shows the mean EEG power spectrum of 26 age-matched healthy controls, whereas the *dotted line* shows the preoperative EEG power spectrum of the patient.

Neurosurgical Procedure

The bilateral CLT procedure using the MRgFUS was performed in a 3-T MRI system (GE Discovery 750, GE Healthcare) using the ExAblate Neuro device (InSightec). Target reconstruction and accuracy determination technique was described in detail in prior publications.[28–30] As mentioned previously,[31] targeting and coverage of the CLT target evolved over the years. In the present case, the target was determined using the Morel's Atlas of the human thalamus and basal ganglia, with one sonication spot placed 2 mm anterior to the posterior commissure, 8 mm lateral to the medial thalamic border, and 6 mm dorsal to the intercommissural plane on both sides.

Sonication parameters used to achieve final temperatures (i.e., to reach thermal doses of at least 240 cumulative equivalent minutes over 43°C on focal point) were 950 W and 17 to 20 seconds on the right and 950 to 1050 W and 17 seconds on the left CLT.

MRI T2 target reconstructions at 48 hours after MRgFUS CLT showed lesion volumes of 67 mm^3 for the right-sided and 141 mm^3 for the left-sided CLT (Fig. 2).

Postoperative Evolution

There were no postoperative side-effects, and the Montreal Cognitive Assessment remained unchanged (30/30). Three months after the intervention, the patient reported a single episode of a typical CH attack with a strong agitation. He recovered spontaneously after 20 minutes. In the following months, 1 to, rarely, 2 headache episodes per week without accompanying vegetative phenomena occurred. Nonpharmacological measures such as walking in nature often helped when he experienced slight prodromas to prevent a pain attack. If not, sumatriptan injections quickly interrupted the beginning attack. The patient discontinued the basic medication with ergotamine/caffeine 2 months after the surgical intervention. Three months after the intervention, the patient estimated his improvement in quality of life to be 80% to 90%, and he had gained 60% independence.

During the following 6 years, the patient consulted once for increasing tension-type headache. He was diagnosed with medication-overuse headache.[32] On his demand, he was hospitalized for 7 days for weaning off the sumatriptan. He was prescribed magnesium

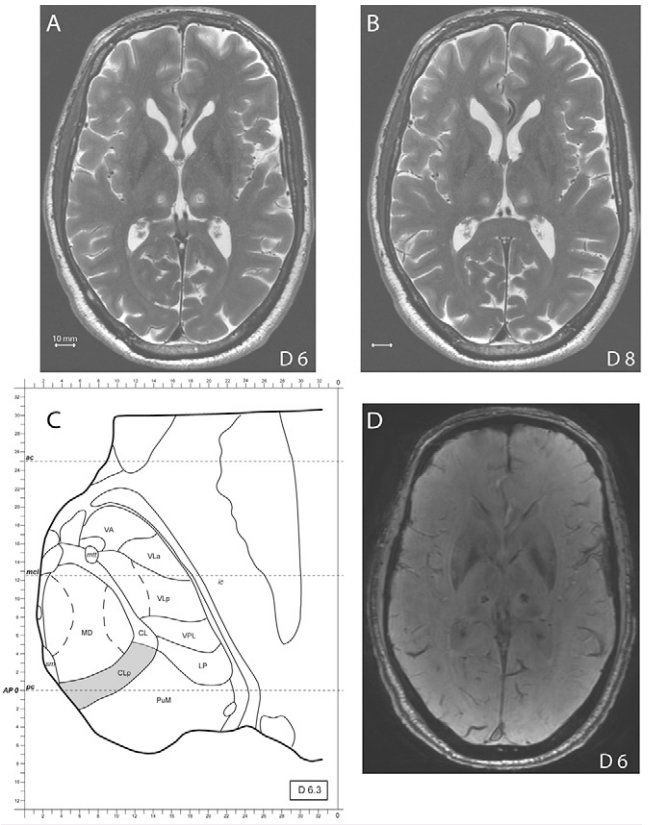

FIG. 2. Axial T2-weighted MR images (**A and B**) obtained 2 days after treatment, 6 and 8 mm dorsal to the intercommissural plane of a bilateral MRgFUS CLT. Modified atlas map (**C**) from Morel's atlas 6.3 mm dorsal to the intercommissural plane with the posterior central lateral nucleus (CLp) in *gray*. ac = anterior commissure; IC = internal capsule; LP = lateral posterior nucleus; MD = mediodorsal nucleus; mtt = mammillothalamic tract; pc = posterior commissure; PuM = medial pulvinar; VA = ventral anterior nucleus; VLa = ventral lateral anterior nucleus; VLp = ventral lateral posterior nucleus; VPL = ventral posterior lateral nucleus. Axial MR susceptibility-weighted angiogram (**D**) obtained 2 days after lesioning.

2 × 300 mg, amitriptylin 25 mg, and trazodone 50 mg daily for a few months.

At the last follow-up 6 years after bilateral CLT, the patient was completely free from any CH attacks. He still reported occasional tension headaches, which he mostly could manage with nonpharmaceutical measures. Exceptionally, the addition of paracetamol 500 mg was required. He is fully independent and without health restrictions. He was also free from depression and anxiety. In the postoperative EEG examination at 3 months, a normalization of cortical activity in the beta-2 and gamma-frequencies could be observed. The overactivity of other frequency domains remained unchanged as compared to their preoperative state. These EEG-findings were practically unchanged at 6 years after the intervention (Fig. 1).

Discussion

Our patient presented with a typical episodic cluster headache that fulfilled all diagnostic criteria: intense, strictly right-sided pain attacks on the first and second branch of the trigeminal nerve lasting up to 90 minutes up to 7 times/day, clear-cut vegetative and ipsilateral accompanying symptoms, strong agitation, episodic occurrence, and respect of the circadian rhythm. As frequently described in cluster headache patients, there was a psychiatric comorbidity as he suffered from an episodic depression years before developing CH. A predisposing factor was smoking, but the patient stopped smoking 4 years after the onset of symptoms.

The neurosurgical treatment of neurogenic pain with medial thalamotomies has a long history since the early 1950s.[33] We have reactualized this approach on histological, physiological, and clinical basis since the late 1980s.[24] The discovery by Lenz et al.[34] in the lateral thalamus (ventroposterior complex) and by Jeanmonod et al. in the medial thalamus of single unit activities identified as low-threshold calcium spike (LTS) bursts by Llinas and coworkers[35] has allowed to propose a thalamic pathophysiological concept for the appearance of neurogenic pain.[22] This thalamic concept was expanded by including the tight feedback loop interactions between thalamus and cortex according to the physiological and MEG data of Llinas and his group. This expanded concept was named thalamocortical dysrhythmia (TCD).[36] The TCD neurogenic pain mechanism is initiated by a peripheral or a central lesion, which leads to deafferentation of excitatory inputs onto thalamic relay cells. Deafferentation of excitatory inputs to the thalamus results in disfacilitation and thalamic cell membrane hyperpolarization. In the hyperpolarized state, deinactivation of calcium T-channels causes thalamic relay neurones to fire LTS bursts at 4 Hz.[22] This causes the associated cortical areas to discharge at 4 Hz. Divergent TC projections provide the anatomical substrate for coherent diffusion of low frequency EEG activity to an increasing number of neighboring thalamic nuclei and cortical areas. The final step toward production of neurogenic pain is related to the reciprocal corticocortical inhibition mediated by GABAergic interneurons, a general feature of cortical organization. The cortical poles of TC modules in theta mode exert less GABAergic corticocortical collateral inhibition on neighboring high frequency cortical areas, which are thereby released and become overactive. This event is called an edge effect.[36] Thus, an increase of high frequency activity in cortical areas of the pain network can give rise to pain, explaining the paradox of a deactivation of the thalamus leading to a cortical activation.

The mentioned LTS burst activities were found concentrated in a specific part of the medial thalamus, the posterior portion of the central lateral nucleus (CLp),[22] which allowed us to refine and base the medial thalamic location of the target on a physiopathological criterion. The intervention was thus named CLT.[24] Its efficiency against neuropathic pain has been published as well as its sparing of sensory, motor, and cognitive functions.[23,37]

Observations

Interestingly, our patient experienced pins-and-needles and burning pain qualities in addition to the more classical tension, crushing, tearing, and throbbing qualities. These are typical neurogenic pain qualities. Second, his quantitative EEG showed a clear-cut, statistically significant overactivity in the delta, theta, alpha, and beta 1 frequency domains, identical with the spectral profile we see in patients with neurogenic pain. Finally, we made the observation on Fig. 2 of the detailed review of May on CH[17] that two of the presented positron emission tomography activations during CH pain attacks were in fact localized in the inferoposteromedial part of the thalamus, close to or maybe even on the parafascicular nucleus. This other medial thalamic nucleus is located just antero-medially to the CLp. We found in it scarce LTS burst activities.[38] These observations speak in favor of a possible common or similar pathophysiology for neurogenic pain and CH.

As mentioned above, the initiating factor for the development of CH has not yet been identified. The fact that most CHs develops unilaterally obliges one to consider the two described TC systems and not to assign CH to a source located exclusively inside the bilaterally organized paralimbic system.

Considering the therapy-refractory, desperate situation of our patient and the observations described above, we decided to perform a bilateral CLT using the MR-guided focused ultrasound technology. CLT is performed bilaterally as a routine. This can be done without risk for side-effects, in correlation with the observation that more than 99% of recorded CLp neurons display a loss of receptive fields, indicating a state of functional block.[22] In other words, the CLp has lost its useful role along the development of the TCD and has become disturbing pathophysiologically and useless functionally. This correlates with the well-documented absence of any motor, sensory, or cognitive deficits after CLT. The CLT can also be performed with radiofrequency[24] or Gamma knife.[39,40] To our knowledge, no DBS studies ever targeted the CLp yet.

Lessons

We propose that bilateral CLT may be considered as a possible surgical treatment option against chronic therapy-refractory cluster headache. Its low risk profile and sparing characteristics for motor, sensory, and cognitive functions hold the promise of a safe and sparing treatment, the efficiency of which will need further work to be established.

Acknowledgments

We thank Dr. Payam Pourtehrani and colleagues at Rodiag Diagnostic Centers Solothurn for MR imaging, Dr. Milek Kowalski for internal medicine support, Tanja Thalmann for nursing care, and Franziska Rossi for administrative support.

References

1. May A. Cluster headache: pathogenesis, diagnosis, and management. *Lancet.* 2005;366(9488):843–855.
2. Bahra A, May A, Goadsby PJ. Cluster headache: a prospective clinical study with diagnostic implications. *Neurology.* 2002;58(3):354–361.
3. Rozen TD, Fishman RS. Cluster headache in the United States of America: demographics, clinical characteristics, triggers, suicidality, and personal burden. *Headache.* 2012;52(1):99–113.
4. Russell MB. Epidemiology of cluster headache. In: Leone M, May A, eds. *Cluster Headache and Other Trigeminal Autonomic Cephalgias*. Springer International Publishing; 2020:7–10.
5. Leone M, Giustiniani A, Cecchini AP. Cluster headache: present and future therapy. *Neurol Sci.* 2017;38(suppl 1):45–50.
6. Joshi S, Rizzoli P, Loder E. The comorbidity burden of patients with cluster headache: a population-based study. *J Headache Pain.* 2017; 18(1):76.
7. O'Connor E, Simpson BS, Houlden H, Vandrovcova J, Matharu M. Prevalence of familial cluster headache: a systematic review and meta-analysis. *J Headache Pain.* 2020;21(1):37.
8. Rozen TD. Cluster headache clinical phenotypes: tobacco nonexposed (never smoker and no parental secondary smoke exposure as a child) versus tobacco-exposed: results from the United States Cluster Headache Survey. *Headache.* 2018;58(5):688–699.
9. Lund N, Petersen A, Snoer A, Jensen RH, Barloese M. Cluster headache is associated with unhealthy lifestyle and lifestyle-related comorbid diseases: results from the Danish Cluster Headache Survey. *Cephalalgia.* 2019;39(2):254–263.
10. May A, Schwedt TJ, Magis D, Pozo-Rosich P, Evers S, Wang SJ. Cluster headache. *Nat Rev Dis Primers.* 2018;4(1):1–17.
11. Finnerup NB, Attal N, Haroutounian S, et al. Pharmacotherapy for neuropathic pain in adults: a systematic review and meta-analysis. *Lancet Neurol.* 2015;14(2):162–173.
12. Nowacki A, Schober M, Nader L, et al. Deep brain stimulation for chronic cluster headache: meta-analysis of individual patient data. *Ann Neurol.* 2020;88(5):956–969.
13. Leone M, Proietti Cecchini A, Messina G, Franzini A. Long-term occipital nerve stimulation for drug-resistant chronic cluster headache. *Cephalalgia.* 2017;37(8):756–763.
14. Jürgens TP, Barloese M, May A, et al. Long-term effectiveness of sphenopalatine ganglion stimulation for cluster headache. *Cephalalgia.* 2017;37(5):423–434.
15. Liu SC, Kao MC, Huang YC, Su WF. Vidian neurectomy for management of chronic cluster headache. *Neurosurgery.* 2019;84(5): 1059–1064.
16. Yuan H, Silberstein SD. Vagus nerve stimulation and headache. *Headache.* 2017;57(suppl 1):29–33.
17. Hoffmann J, May A. Diagnosis, pathophysiology, and management of cluster headache. *Lancet Neurol.* 2018;17(1):75–83.
18. Ferraro S, Nigri A, Bruzzone MG, et al. Cluster headache: insights from resting-state functional magnetic resonance imaging. *Neurol Sci.* 2019;40(suppl 1):45–47.
19. May A. New insights into headache: an update on functional and structural imaging findings. *Nat Rev Neurol.* 2009;5(4):199–209.
20. Ekbom K. Evaluation of clinical criteria for cluster headache with special reference to the classification of the International Headache Society. *Cephalalgia.* 1990;10(4):195–197.
21. Chu MK, Kim BS, Chung PW, et al. Clinical features of cluster headache without cranial autonomic symptoms: results from a prospective multicentre study. *Sci Rep.* 2021;11(1):6916.
22. Jeanmonod D, Magnin M, Morel A. Low-threshold calcium spike bursts in the human thalamus. Common physiopathology for sensory, motor and limbic positive symptoms. *Brain.* 1996;119(Pt 2):363–375.
23. Jeanmonod D, Sarnthein J, Magnin M, et al. Chronic neurogenic pain: thalamocortical dysrhythmic mechanisms and their surgical treatment. *Thalamus Relat Syst.* 2005;3(1):63–70.
24. Jeanmonod D, Morel A. The central lateral thalamotomy for neuropathic pain. In: Lozano AM, Gildenberg PL, Tasker RR, eds. *Textbook of Stereotactic and Functional Neurosurgery.* Springer; 2009:2081–2096.
25. Richardson DE. Thalamotomy for intractable pain. *Confin Neurol.* 1967; 29(2):139–145.
26. Leone M, Ferraro S, Proietti Cecchini A. The neurobiology of cluster headache. In: Swaab DF, Buijs RM, Kreier F, Lucassen PJ, Salehi A, eds. *Handbook of Clinical Neurology. Vol 182. The Human Hypothalamus: Neuropsychiatric Disorders.* Elsevier; 2021:401– 414.
27. Sarnthein J, Stern J, Aufenberg C, Rousson V, Jeanmonod D. Increased EEG power and slowed dominant frequency in patients with neurogenic pain. *Brain.* 2006;129(Pt 1):55–64.
28. Jeanmonod D, Werner B, Morel A, et al. Transcranial magnetic resonance imaging-guided focused ultrasound: noninvasive central lateral thalamotomy for chronic neuropathic pain. *Neurosurg Focus.* 2012;32(1):E1.
29. Moser D, Zadicario E, Schiff G, Jeanmonod D. Measurement of targeting accuracy in focused ultrasound functional neurosurgery. *Neurosurg Focus.* 2012;32(1):E2.
30. Moser D, Zadicario E, Schiff G, Jeanmonod D. MR-guided focused ultrasound technique in functional neurosurgery: targeting accuracy. *J Ther Ultrasound.* 2013;1:3.
31. Gallay MN, Moser D, Jeanmonod D. MR-guided focused ultrasound central lateral thalamotomy for trigeminal neuralgia. *Front Neurol.* 2020;11:271.
32. Headache Classification Committee of the International Headache Society (IHS). The International Classification of Headache Disorders. 3rd edition. *Cephalalgia*. 2018;38(1):1–211.

33. Jeanmonod D, Magnin M, Morel A. A thalamic concept of neurogenic pain. In: *Proceedings of the 7th World Congress on Pain. Progress in Pain Research and Management.* IASP Press; 1994:767–787.
34. Lenz FA, Kwan HC, Dostrovsky JO, Tasker RR. Characteristics of the bursting pattern of action potentials that occurs in the thalamus of patients with central pain. *Brain Res.* 1989;496(1-2):357–360.
35. Llinás R, Jahnsen H. Electrophysiology of mammalian thalamic neurones in vitro. *Nature.* 1982;297(5865):406–408.
36. Llinás RR, Ribary U, Jeanmonod D, Kronberg E, Mitra PP. Thalamocortical dysrhythmia: a neurological and neuropsychiatric syndrome characterized by magnetoencephalography. *Proc Natl Acad Sci U S A.* 1999;96(26):15222–15227.
37. Pirrotta R, Jeanmonod D, McAleese S, et al. Cognitive functioning, emotional processing, mood, and personality variables before and after stereotactic surgery: a study of 8 cases with chronic neuropathic pain. *Neurosurgery.* 2013;73(1):121–128.
38. Jeanmonod D, Magnin M, Morel A. Thalamus and neurogenic pain: physiological, anatomical and clinical data. *Neuroreport.* 1993; 4(5):475–478.
39. Young RF, Jacques DS, Rand RW, Copcutt BR. Medial thalamotomy with the Leksell Gamma Knife for treatment of chronic pain. In: Lindquist C, Kondziolka D, Loeffler JS, eds. *Advances in Radiosurgery.* Springer; 1994:105–110.
40. Franzini A, Attuati L, Zaed I, et al. Gamma Knife central lateral thalamotomy for the treatment of neuropathic pain. *J Neurosurg.* 2020;135(1):1–9.

Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Magara, Jeanmonod. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: Magara, Gallay. Critically revising the article: Magara, Gallay, Jeanmonod. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Magara. Administrative/technical/material support: Moser, Jeanmonod. Study supervision: Jeanmonod.

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