Update on the pathophysiology of cluster headache: imaging and neuropeptide studies

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Objective: Cluster headache (CH) is the most severe primary headache condition. Its pathophysiology is multifaceted and incompletely understood. This review brings together the latest neuroimaging and neuropeptide evidence on the pathophysiology of CH.

Methods: A review of the literature was conducted by searching PubMed and Web of Science. The search was conducted using the following keywords: imaging studies, voxel-based morphometry, diffusion-tensor imaging, diffusion magnetic resonance imaging, tractography, connectivity, cerebral networks, neuromodulation, central modulation, deep brain stimulation, orexin-A, orexin-B, tract-based spatial statistics, single-photon emission computer tomography studies, positron-emission tomography, functional magnetic resonance imaging, magnetic resonance spectroscopy, trigeminovascular system, neuropeptides, calcitonin gene-related peptide, neurokinin A, substance P, nitric oxide synthase, pituitary adenylate cyclase-activating peptide, vasoactive intestinal peptide, neuropeptide Y, acetylcholine, noradrenaline, and ATP. “Cluster headache” was combined with each keyword for more relevant results. All irrelevant and duplicated records were excluded. Search dates were from October 1976 to May 2018.

Results: Neuroimaging studies support the role of the hypothalamus in CH, as well as other brain areas involved in the pain matrix. Activation of the trigeminovascular system and the release of neuropeptides play an important role in CH pathophysiology. Among neuropeptides, calcitonin gene-related peptide, vasoactive intestinal peptide, and pituitary adenylate cyclase-activating peptide have been reported to be reliable biomarkers for CH attacks, though not specific for CH. Several other neuropeptides are involved in trigeminovascular activation, but the current evidence does not qualify them as reliable biomarkers in CH.

Conclusion: CH has a complex pathophysiology and the pain mechanism is not completely understood. Recent neuroimaging studies have provided insight into the functional and structural network bases of CH pathophysiology. Although there has been important progress in neuropeptide studies, a specific biomarker for CH is yet to be found.

Keywords: voxel-based morphometry, single-photon emission computer tomography, positron-emission tomography, functional magnetic resonance imaging, calcitonin gene-related peptide, pituitary adenylate cyclase-activating peptide

Introduction

Cluster headache (CH) is the most severe primary headache disorder.1 CH has been called “suicide headache”, because some patients have taken their lives during an attack or in anticipation of an attack.2 According to the International Classification of Headache Disorders, CH is defined as a unilateral condition,1 but bilateral attacks3 or alternating attack...
sides can occur. CH is associated with ipsilateral conjunctival injection, lacrimation, nasal congestion, rhinorrhea, forehead and facial sweating, miosis, ptosis and/or eyelid edema, and/or with restlessness or agitation. A CH attack can last 15 minutes to 3 hours, occurring from every other day to eight times a day. The ways brain function are explored have revolutionized the understanding of pain mechanisms in headache disorders. Neuroimaging techniques and neuropeptide studies in CH are included in this review.

Methods
A review of the literature was carried out by searching PubMed and Web of Science. The search was conducted using the following keywords: imaging studies, voxel-based morphometry, diffusion-tensor imaging, diffusion magnetic resonance imaging, tractography, connectivity, cerebral networks, neuromodulation, central modulation, deep-brain stimulation, orexin-A, orexin-B, tract-based spatial statistics, single-photon-emission computed tomography studies, positron-emission tomography, functional magnetic resonance imaging, magnetic resonance spectroscopy, trigeminovascular system, neuropeptides, calcitonin gene-related peptide, neurokinin A, substance P, nitric oxide synthase, pituitary adenylate cyclase-activating peptide, vasoactive intestinal peptide, neuropeptide Y, acetylcholine, noradrenaline, and ATP. “Cluster headache” was combined with each keyword for more relevant results (eg, “cluster headache” + “imaging studies”, “cluster headache” + “neuropeptides”). All irrelevant and duplicated records were excluded from consideration. Works published from October 1976 to September 2018 are presented in the current review.

Results
Imaging studies in CH
The first functional imaging studies in CH used single-photon-emission computed tomography (SPECT). They were followed by positron-emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies. Structural imaging studies used voxel-based morphometry (VBM), diffusion-tensor imaging (DTI), tract-based spatial statistics (TBSS), and diffusion tractography. The findings of imaging studies are summarized in Table 1.

Structural studies
VBM
VBM is a structural imaging technique that allows investigation of focal differences in brain anatomy, and it is mainly used to identify gray-matter alterations. Used in a pioneering study by May et al, VBM inspired many researchers to use the technique in the study of pain. It showed the involvement of the posterior hypothalamus in the pathophysiology of CH. The study, conducted on 25 patients, detected significant structural differences (increase in volume) in gray-matter density among patients with CH compared to controls. A PET study on the same patient cohort showed activation of the same brain area. These findings led to the conclusion that the changes might be permanent and not a reaction to pain, showing a clear correlation between the structural and functional changes in CH. Matharu, who reproduced the study, found no alterations in gray or white matter, suggesting that the initial finding might have been due to methodological limitations.

A more recent study, carried out by Absinta et al, showed alterations in brain structures involved in pain processing (reduced gray-matter volume in the right posterior cingulate cortex, the head of the right caudate nucleus, right thalamus, left inferior parietal lobe, right middle temporal gyrus, left insula, right precentral gyrus, right precentral gyrus, and bilateral frontal gyrus). Using the same imaging technique, reduction in gray matter in frontal areas was detected in 49 patients with CH, findings interpreted as dysfunction of the descending pain-modulation systems in CH. The same study detected gray-matter increase in the anterior cingulate gyrus, insula, and fusiform gyrus, changes that could represent compensation mechanisms or neuroplasticity. The largest VBM study showed that brain alterations (temporal lobe, hippocampus, insular cortex, and cerebellum) were related to disease burden and variable in relation to the pain state.

Although multiple studies have explored the role of the posterior hypothalamus in CH, a recent study showed enlargement of the anterior hypothalamus in patients with both episodic and chronic CH compared with patients with migraine. Located in the anterior hypothalamus, the supraoptic nucleus, which is the endogenous biological clock, might cause the circadian and circannual periodicity that characterizes CH.

DTI/TBSS/tractography
DTI is an MRI technique used to estimate the axonal white-matter organization of the brain. The data are collected by diffusion weighted imaging. The main parameters measured with DTI are fractional anisotropy and diffusivity. Anisotropy is the property of being directionally dependent, which implies different properties in different directions, as opposed to isotropy.
Table 1 Neuroimaging and biochemical studies

| Study                      | Modality/method                  | Subjects and diagnosis | Main findings                                                                 |
|----------------------------|----------------------------------|------------------------|------------------------------------------------------------------------------|
| Structural studies         |                                   |                        |                                                                              |
| May et al12                | sMRI-T1W/VBM                     | 25 ECH                 | Increase in bilateral posterior hypothalamic GM                               |
| Matharu13                  | sMRI-T1W/VBM                     | 66 ECH                 | No significant changes in GM and WM                                             |
| Owen et al20               | DW-MRI/probabilistic tractography | 1 CCH                  | No CH attacks at 8 months after the DBS electrode was placed 6 mm posterior to the hypothalamus, 2 mm lateral, and 8 mm below the midcommissural point |
| Absinta et al14            | sMRI-T1W/VBM and TBSS            | 15 ECH                 | 1. GM decrease in the pain network  
2. GM increase in the right cuneus  
3. No changes seen within the hypothalamus                                      |
| Teepker et al22            | sMRI-DTI/TBSS                    | 7 ECH                  | Widespread WM alterations involved in trigeminal/nociceptive processing        |
| Seifert et al25            | sMRI-T1W/whole-brain surface-based comparison of cortical thickness | 12 ECH                 | Cortical thinning in the contralateral angular and precentral gyrus           |
| Yang et al15               | sMRI-T1W/VBM                     | 49 ECH                 | 1. GM-volume reduction in frontal areas  
2. GM increase in the ACC, fusiform gyrus, and insula (longitudinal analysis) |
| Szabo et al23              | sMRI-DTI/TBSS                    | 13 ECH                 | Widespread reduction in FA and increase in diffusivity (contralateral dominance) |
| Naegel et al18             | sMRI-T1W/VBM                     | 68 ECH, 23 CCH         | GM-volume alterations in the temporal lobe, hippocampus, insular cortex, and cerebellum |
| Chou et al20               | sMRI-DTI/TBSS                    | 17 ECH                 | High diffusivity in the left frontal gyrus and lower diffusivity in the right parahippocampal gyrus |
| Kiraly et al24             | sMRI-T1W and DTI/FSL             | 22 ECH                 | 1. Increased FA of the right amygdala  
2. Increased diffusivity in the right caudate  
3. High radial diffusivity and lower anisotropy in the right pallidus |
| Arkink et al17             | sMRI-T1W/VBM                     | 24 ECH, 23 CCH, 14 Probable CH | Increased volume of the anterior hypothalamus in patients with ECH and CCH; similar trends, but not significant in patients with probable CH |
| Akram et al26              | DW-MRI/VBM/probabilistic diffusion tractography | 7 CCH | The DBS-activated area posterior to the hypothalamus in the ventral tegmental area lies on the tract that connects the hypothalamus, prefrontal, and temporal regions with brain-stem area |
| Seijo-Fernandez et al27    | DW-MRI/probabilistic diffusion tractography | 15 CCH | Projections between the DBS target areas and ipsilateral cerebellum and reticular nucleus |
| Functional studies         |                                   |                        |                                                                              |
| Norris et al16             | SPECT/ROI                        | 1 ECH                  | No changes in mean CBF                                                        |
| Sakai and Meyer*           | SPECT/ROI                        | 8 ECH                  | Increased CBF                                                                |
| Henry et al17              | SPECT/ROI                        | 3 ECH                  | No changes in mean CBF                                                        |
| Nelson et al11             | SPECT/ROI                        | 26 ECH                 | Variable changes in mean CBF (increase or decrease)                           |
| Krabbe et al13             | SPECT/ROI                        | 9 ECH, 9 CCH           | No changes in mean CBF                                                        |
| Di Piero et al20           | SPECT/ROI                        | 7 ECH                  | Decreased CBF in the posterior parietal cortex and thalamus contralateral to the pain side |
| Hsieh et al8               | PET/VBA and ROI                  | 7 ECH                  | 1. Decreased rCBF in the frontal cortex, posterior parietal cortex, and occipitotemporal regions  
2. Increased rCBF in the ACC, frontal cortex, insula, putamen, and temporopolar region with preference of the right hemisphere |
| May et al12                | PET/VBA                          | 9 CCH                  | 1. Exclusive activation during CH attacks of the inferior hypothalamic gray matter ipsilateral to the headache side  
2. Increased rCBF in the ventroposterior thalamus, ACC, and insula bilaterally |
| May et al12                | PET/VBM                          | 17 ECH                 | Activation of inferior posterior hypothalamic ipsilateral to the headache side |
| May et al23                | PET and MRA/VBA                  | 17 ECH                 | 1. Activation of inferior posterior hypothalamic, frontal lobes, insula bilaterally, ACC bilaterally, ipsilateral thalamus, ipsilateral basal ganglia, and contralateral inferior frontal cortex  
2. Increased CBF in the ICA ipsilateral to the headache side |

(Continued)
Fractional anisotropy is a scalar value from zero to one and describes the anisotropy of a diffusion process. Fractional anisotropy with a value of zero means the diffusion is isotropic (unrestricted or equally restricted in all directions). A value of one means that the diffusion affects one axis and is restricted along the other axis. Statistical analysis is performed using TBSS. TBSS uses nonlinear image transformation that combines...
the strength of both voxelwise and tractography-based analyses.\textsuperscript{21}

The VBM study performed by Absinta et al used a DTI/TBSS analysis on the same sample of patients, but no significant change in fractional anisotropy or diffusivity was found.\textsuperscript{14} Another three studies that used DTI to explore brain changes in CH found widespread alterations in the pain-processing system (“pain matrix”).\textsuperscript{20,22,23} Interictal alterations in subcortical structures are present in CH (right amygdala, right caudate, right pallidus).\textsuperscript{24} Some of the microstructural changes are related to lifetime disease burden, suggesting that recurring painful episodes might trigger maladaptive plasticity or degenerative processes.\textsuperscript{24}

Diffusion tractography is used to identify brain connectivity along white-matter pathways.\textsuperscript{25} Tractography studies have shown that the deep brain stimulation (DBS)-activated area lies in the ventral tegmental area, posterior to the hypothalamus,\textsuperscript{26–28} and projects to the ipsilateral cerebellum and reticular nucleus.\textsuperscript{28,29}

Other structural imaging studies
Seifert et al conducted a high-resolution T1-weighted MRI study and performed whole-brain surface-based comparison of cortical thickness.\textsuperscript{30} The study showed cortical thickening in patients with CH, implying involvement of the cortical structures in the pathogenesis of CH.\textsuperscript{30}

Functional studies
SPECT
SPECT was used as an early neuroimaging technique to evaluate cerebral blood flow by \textsuperscript{133}Xe inhalation. Studies have shown varied results: some reported increases,\textsuperscript{6,31} others decreases,\textsuperscript{31} and some no changes\textsuperscript{5,7,32} in cerebral blood flow. The last SPECT study showed reduced cerebral blood flow in the thalamus and posterior parietal areas contralateral to the pain side, hypothesizing early involvement of these brain areas in CH pathophysiology.\textsuperscript{31}

PET
PET is a nuclear medicine magnetic imaging technique that detects $\gamma$-rays emitted by a positron-emitting radionuclide (tracer). The biological molecule chosen for PET is fluoro-oxyglucose, an analog of glucose.\textsuperscript{34} Hsieh et al conducted the first nitroglycerin-induced PET study on seven patients with episodic CH in 1996, and showed activation of brain areas involved in central nociception with preference for the right hemisphere.\textsuperscript{8} Although the initial PET study did not show activation of the hypothalamus, a study conducted by May et al 2 years later showed activation of the inferior hypothalamic gray matter ipsilateral to the headache side during nitroglycerine-induced attacks.\textsuperscript{9} A later PET/magnetic resonance angiography study by the same group on a larger population of 17 patients with episodic CH showed activation of the inferior posterior hypothalamus and brain areas involved in pain processing.\textsuperscript{35} Significant dynamic changes in brain metabolism during and outside CH attacks were detected by three PET studies carried out by Sprenger et al.\textsuperscript{36–38}

fMRI
fMRI measures brain activity by detecting changes associated with blood flow, and relies on the fact that blood flow and cerebral activation are coupled. When a brain area is active, the blood flow to that area increases.\textsuperscript{39} The primary form of fMRI uses blood-oxygen-level-dependent contrast and measures changes in blood flow and tissue oxygenation.\textsuperscript{39} Resting-state fMRI is a technique that assesses baseline brain activity when subjects are not performing any task, in contrast to task-specific fMRI.\textsuperscript{40} In the first fMRI study, Morelli et al showed activation of the hypothalamus during CH attacks and activation of other brain areas involved in pain processing.\textsuperscript{16} The role of the hypothalamus in the pathophysiology of CH was strengthened by several studies that found abnormal functional connectivity of the hypothalamus.\textsuperscript{31,41–44} Involvement of the pain matrix and nontraditional pain-processing areas (eg, salience networks, occipital area, cerebellar network) were also found.\textsuperscript{40,44} Metabolic normalization in the pain-matrix areas and absent short-term changes induced by occipital nerve stimulation (ONS) might support the hypothesis that ONS, a symptomatic treatment for CH, works through slow neuromodulation.\textsuperscript{35}

Biochemical studies
31P magnetic resonance spectroscopy (MRS) can be used as a noninvasive tool for measuring relative intracellular concentrations of phosphorus containing metabolites in different organs.\textsuperscript{46} Montagna et al conducted the first 31P-MRS study on 14 patients with CH and showed abnormalities in brain-energy metabolism, with reduced phosphocreatine levels, increased ADP, reduced phosphorylation potential, and high relative rate of ATP biosynthesis.\textsuperscript{47} A few years later, Lodi et al showed reduced cytosolic free Mg$^2+$ and free energy released by the reaction of ATP hydrolysis.\textsuperscript{48} The first in vivo proton MRS (1H-MRS) studies to show the involvement of the hypothalamus in CH pathophysiology were performed in 2006.\textsuperscript{49,50} 1H-MRS allows noninvasive measurement of signal
intensities derived from \( N \)-acetylaspartate, creatine, and phosphocreatine and choline-containing compounds.\(^{31}\) The studies showed reduced hypothalamic \( N \)-acetylaspartate:creatine\(^{49,50}\) and choline:creatine ratios\(^{48}\) in patients with CH.

**Trigeminovascular pain pathways and neuropeptides**

**Anatomy of the trigeminovascular pain pathways**

The trigeminovascular system includes the trigeminal ganglion, the meningeal vasculature, and distinct nuclei of the brain stem, thalamus, and the somatosensory cortex (Figure 1).\(^{52}\) Pseudounipolar primary afferent fibers from the trigeminal ganglion synapse on intra- and extracranial structures.\(^{52}\) Nociceptive fibers innervating the pial, arachnoid, and dural blood vessels, including large cerebral arteries, superior sagittal sinus, and middle meningeal artery, arise from the trigeminal nerve, mostly V1.\(^{53}\) On the other hand, sensory fibers innervating the posterior fossa and basilar arteries are located in the C1–C3 dorsal root ganglia.\(^{54}\) Projections from the trigeminal ganglion and upper cervical nerve roots converge at the trigeminocervical complex. Second-order neurons from the trigeminocervical complex ascend in the trigeminothalamic tract and synapse with third-order neurons.\(^{53}\) The third-order thalamocortical neurons synapse with a complex cortical network including the primary and secondary motor, sensory, and visual areas.\(^{53}\) There are direct and indirect ascending projections to the hypothalamus, periaqueductal gray, and locus coeruleus.\(^{53}\) There is a reflex connection from the trigeminal nucleus to the superior salivatory nucleus, which projects via sphenopalatine ganglion.\(^{53}\) Additional ascending projections exist to the insula, retrosplenial cortex, ectorhinal areas, rostral ventromedial medulla, parietal associations, and auditory areas.\(^{53}\)

The thalamus is the relay center involved in the modulation and processing of all incoming sensory information.\(^{56}\) The pain matrix, which includes the thalamus, primary and secondary somatosensory areas, anterior cingulate gyrus, and prefrontal cortex, is active during nociceptive processing.\(^{56}\) Furthermore, indirect projections from the trigeminal nucleus to the amygdala and hippocampus are likely to be involved in the processing of cognitive and affective responses to pain.\(^{57}\)

**Activation of the trigeminovascular system**

In vivo human studies have shown activation of the trigeminovascular system during acute CH attacks,\(^{58}\) with distribution of pain in the ophthalmic division of the trigeminal nerve.\(^1\) Parasympathetic activation as a component of CH attacks

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**Figure 1** Ascending pathways of the trigeminovascular system.

Notes: Reproduced from Goodbody PJ, Holland PR, Martins-Oliveira M, Hoffmann J, Schankin C, Akerman S. Pathophysiology of migraine: a disorder of sensory processing. Physiol Rev. 2017;97(2):553–622.\(^{33}\)

Abbreviations: TCC, trigeminocervical complex; SuS, superior salivatory nucleus; LC, locus coeruleus; Ins, insula; RS, retrosplenial; Ect, ectorhinal; RVM, rostral ventromedial medulla; PTA, parietal association area; Au, auditory association area; TG, trigeminal ganglion; SPG, sphenopalatine ganglion; PAG, periaqueductal grey; M1/M2, primary and secondary motor area; S1/S2, primary and secondary sensory areas; V1/V2, primary and secondary visual areas.
involves the activation of the trigeminal-autonomic reflex, and manifests clinically as lacrimation, nasal congestion, and rhinorrhea. Activation of the parasympathetic fibers is mediated through the facial nerve. Sphenopalatine ganglion stimulation is known to relieve CH pain. The sympathetic overactivity could be explained by dilatation of the carotid artery secondary to parasympathetic activation and subsequent compression on the periarterial plexus of sympathetic fibers. However, parasympathetic overactivity alone could be responsible for the ocular sympathetic deficit. Neuropeptides involved in trigeminovascular system activation

Activation of the trigeminovascular system leads to neuropeptide release. Nerve fibers are classified based on their neuropeptide content. Trigeminal sensory fibers contain calcitonin gene-related peptide (CGRP), neurokinin A, substance P, nitric oxide synthase, and pituitary adenylate cyclase-activating peptide (PACAP), parasympathetic nerve fibers are rich in vasoactive intestinal peptide (VIP), neuropeptide Y, acetylcholine, nitric oxide synthase, and PACAP, and sympathetic nerve fibers contain norepinephrine, ATP, and neuropeptide Y (Table 2).

Table 2 Craniovascular nerve fibers and their vasoactive neuropeptides

| Neuropeptide/neurotransmitter | Role of neuropeptide/neurotransmitter |
|-------------------------------|--------------------------------------|
| **Trigeminal sensory nerve fibers** |
| Calcitonin gene-related peptide | Vasodilation and plasma extravasation |
| Neurokinin                     | Initiation of expression of cytokines |
| Substance P                    | Vasodilation and plasma extravasation |
|                               | Initiation of expression of cytokines |
| Nitric oxide synthase          | Regulates blood flow (vasodilatation) |
|                               | Prevents platelet activation |
|                               | Inhibits monocyte adhesion and leukocyte function |
| Pituitary adenylate cyclase-activating peptide (PACAP) | Vasodilatation |
| **Parasympathetic nerve fibers** |
| Vasoactive intestinal peptide  | Potent vasodilator |
|                               | Proinflammatory and anti-inflammatory effects |
| Neuropeptide Y                 | Vasodilatation |
| Acetylcholine                   | Vasodilatation |
|                               | Mast-cell degranulation |
| Nitric oxide synthase           | Vasodilatation |
| PACAP                          | Vasodilatation |
| **Sympathetic nerve fibers**    |
| Norepinephrine                 | Potent vasoconstrictor |
| ATP                            | Vasoconstriction |
| Neuropeptide Y                 | Vasoconstriction |

Notes: Reproduced from Goadsby PJ, Holland PR, Martins-Oliveira M, Hoffmann J, Schankin C, Aikerman S. Pathophysiology of migraine: a disorder of sensory processing. Physiol Rev. 2017;97(2):553–622.
Neurokinin A
Neurokinin A (formally known as substance K) has an important contribution to nociceptive processing and inflammatory response, initiating the release of cytokines.74 Neurokinin A, together with CGRP and substance P, is released from the caudal trigeminal nucleus of the rat during electrical stimulation of the trigeminal ganglion.75 The main role of neurokinin A is vasodilatation. The order of potency is CGRP > substance P > neurokinin A.58

PACAP
PACAP is involved in the regulation of important biological functions and is located in the brain and peripheral organs, notably the endocrine pancreas, gonads, and respiratory and urogenital tracts.76 PACAP is found in both trigeminal sensory and parasympathetic fibers, and its main role is vasodilatation.77 Although the role of PACAP has been more extensively studied in migraine,78-80 it was shown that PACAP38 is released during CH attacks, with significantly low levels during the interbout period.81

Nitric oxide synthase
Nitric oxide synthases are a family of enzymes catalyzing the production of nitric oxide from L-arginin.82 Nitric oxide is a signaling molecule found in most tissue in the body. Among many other roles, nitric oxide controls neurotransmission and vascular tone.82 Nitric oxide production is correlated with disease activity of inflammatory disorders, such as multiple sclerosis,83 systemic lupus erythematosus,84 and bacterial meningitis.85 Nitric oxide synthase regulates blood flow (vasodilatation), prevents platelet activation, and inhibits monocyte adhesion and leukocyte function.86 Nitrates, which are reduced to nitric oxide in the body, are well-known headache triggers.86 Enhanced nitric levels have been found in the plasma87 and cerebrospinal fluid82 of patients with CH during active and remission periods. It has been shown that genetic variations within the nitric oxide synthase gene are less likely to contribute to CH susceptibility.88

Parasympathetic nerve fibers
VIP
VIP is a peptide hormone of 28 amino-acid residues that belongs to a glucagon/secretin family. VIP is a potent vaso- dilator, and has proinflammatory and anti-inflammatory effects.89 VIP is found in the parasympathetic nervous system and supraoptic nucleus, as well as the digestive and cardiovascular systems.90 Elevated VIP plasma levels have been found during CH attacks and migraine, suggestive of intense parasympathetic activation.72 Serum VIP, but not CGRP, levels seem to reflect the rate of activation of the parasympathetic arm of the trigeminovascular system in migraines,90 but there are no studies that have tested the same in patients with CH.

Neuropeptide Y
Neuropeptide Y is a 36 amino-acid neuropeptide and the most abundant peptide in the central and peripheral nervous systems. Neuropeptide Y is found in a high number of neurons of parasympathetic ganglia, but is produced mainly by the sympathetic nervous system. In the human brain, neuropeptide Y expression is highly concentrated in hypothalamic nuclei, basal ganglia, and the limbic system.92 Neuropeptide Y can modulate nociceptive trigeminovascular transmission in second-order neurons after peripheral systemic administration.93 Its main role is vasoconstriction, although it can also have a vasorelaxant effect.94 Early experiments did not find changes in neuropeptide Y levels in the external jugular vein during CH attacks.72 This may suggest that a more localized locus of release, eg, the hypothalamic nuclei, would not detect neuropeptide Y in the extracranial vessels.

Acetylcholine
Acetylcholine is the neurotransmitter used at the neuromuscular junction, and is released by motor neurons to activate muscles. Acetylcholine is also used as a neurotransmitter in the autonomic nervous system, both as the final product released by the parasympathetic nervous system and as an internal transmitter for the sympathetic nervous system.95 Parasympathetic fibers originating from the sphenopalatine ganglion and trigeminal nerves release acetylcholine, VIP, and PACAP, provoking mast-cell degranulation and additional release of neurotransmitters, or they can directly affect trigeminal nerves inducing nociception.96 It is well known that parasympathetic activation is present in CH and other primary headaches. Acute electrical stimulation of the sphenopalatine ganglion provides significant pain relief and significant and clinically meaningful reduction in CH-attack frequency in some patients.61

Sympathetic nerve fibers
Norepinephrine
Norepinephrine, also called noradrenaline, also produced by locus coeruleus in the pons, is used as a neurotransmitter by the sympathetic ganglia and released into the bloodstream by the adrenal glands. Norepinephrine is a potent vasoconstrictor. Tyrosine,97 tryptamine,98 and tyramine98 metabolism, all involved in norepinephrine production, have been found to be abnormal in patients with chronic CH. A primary autonomic...
dysfunction in CH is also suggested by increased β-receptor response to norepinephrine, as shown by Meyer et al.99

ATP
ATP is a complex chemical compound involved in intracellular energy transfer. ATP has several roles as an excitatory cotransmitter in the peripheral nerves.100 It is stored with noradrenaline in the synaptic vesicles in postganglionic sympathetic fibers and has vasoconstriction properties.100 Existing magnetic spectroscopy studies have shown abnormal energy metabolism in patients with CH.47,48

Orexin A and orexin B
Hypocretin, also known as orexin, is produced in the lateral and posterior hypothalamus. The hypocretin neuropeptide-precursor gene encodes a neuropeptide-precursor protein that gives rise to orexin A and orexin B, and is involved in a wide range of physiological processes, including pain transmission and neuroendocrine and autonomic function.102 HCRTR1 and HCRTR2 are hypocretin receptors. A meta-analysis that included 593 patients with CH and 599 controls from three European studies showed that the 1,246G-A polymorphism (rs2653349) in the HCRTR2 gene may modulate the risk of CH.103-106 In contrast, the largest population-based study, conducted by Weller et al in 2015 on 575 patients with CH and 874 controls, found no evidence for association of rs2653349 and CH, but a positive association was found in the meta-analysis conducted by the same authors on six previously published studies.107 The meta-analysis results should be interpreted with caution, as individual population studies have limited power and thus limited validity.107 A study on Chinese patients conducted by Fan et al (112 patients with CH and 192 controls) did not find a significant association between hypocretin-gene polymorphism and CH.108 Given the inconsistency of the results from reported studies, the exact role of the HCRTR2 gene in CH is yet to be established.

Discussion
Structural and functional imaging studies have revolutionized our understanding of the pathophysiology of CH. Several neuroimaging studies have identified differences between patients with CH and control subjects with respect to brain structure. Neuroimaging studies have shown a clear correlation between the structural and functional changes in CH. The hypothalamus, an important component of the central nervous system that plays a role in homeostasis, autonomic, endocrine function, and nociception,109 has been hypothesized to play an essential role in initiating CH attacks. Neuroimaging findings have determined the use of stereotactic stimulation of the activated brain areas identified by structural and functional imaging. Although previous reports referred to the posterior hypothalamus as the optimal target, tractography studies have shown that the DBS-activated area is not located within the anatomically defined limits of the hypothalamus.26,110,111 The precise anatomical location for DBS refers to the midbrain tegmentum, rather than the posterior hypothalamus.29,111 The neurons in the ventral tegmental area project to multiple brain regions, and are involved in pain modulation, cognition, motivation, and behavioral disorders.112

Neuroimaging studies also implicate other brain areas generally associated with the pain matrix, such as various brain-stem areas, diencephalic structures, prefrontal cortex, basal ganglia, and parts of the limbic system.109 The pain matrix integrates all the sensory, affective, and cognitive responses to pain and becomes active during nociceptive processing.53 These areas are involved in a broad range of chronic painful diseases and are not specific for headache disorders.113 Abnormal metabolism in the perigenual anterior cingulate cortex suggests involvement in the descending antinociceptive processing in patients with episodic CH.38 It is recognized that alterations in the central and descending opioid system contribute to the chronification of pain.114 The microstructural changes present in patients with CH are related to lifetime disease burden, suggesting that recurring painful episodes might trigger maladaptive responses.24

The release of neuropeptides as a consequence of trigeminovascular system activation has been proposed as a pain mechanism in CH and other primary headaches.115 The release of these peptides leads to a series of tissue responses, including arteriolar vasodilatation, plasma protein extravasation, and degranulation of mast cells in their peripheral target tissue.116 Among sensory neuropeptides, peripheral CGRP levels,58,65,66 VIP,91 and PACAP3881 are reported to be good biomarkers of acute CH attacks. Serum VIP, but not CGRP, levels seem to reflect the rate of activation of the parasympathetic arm of the trigeminovascular system in migraine,91 but there are no studies that have tested the same in patients with CH. Several other neuropeptides are involved in trigeminovascular system activation (substance P, neurokinin A, nitric oxide synthase, neuropeptide Y, acetylcholine, norepinephrine, ATP), but the existing evidence does not qualify them as reliable biomarkers in CH. Although there is a real need for biomarkers in CH, the current data must be interpreted with caution. The elevated levels of neuropeptides during CH attacks could only suggest activation of the trigeminovascular system, present in other primary headaches and not specific for CH.
Different sites, such as the ventral tegmental area, occipital nerve, sphenopalatine nerve, and vagus nerve have been recognized as relevant pain pathways in the pathophysiology of CH. Neurostimulation of these pain pathways can influence central neurotransmitters. Invasive neurostimulation techniques are reserved for patients with refractory CH.

**Conclusion**

Neuroimaging studies have reported three major findings: activation of the posterior hypothalamic area during CH attacks, involvement of the pain matrix, and involvement of the central opioid system. It is debatable whether the activation seen in these studies is of the midbrain tegmentum or the posterior hypothalamus. Among neuropeptides, CGRP, VIP, and PACAP38 are reported to be good markers of CH attacks, but they are not specific for CH and can only suggest activation of the trigeminovascular system. Neurostimulation therapies for refractory CH, such as DBS, ONS, and sphenopalatine ganglion stimulation, are important tools in understanding CH pathophysiology.

**Author contributions**

All authors contributed to data analysis, drafting or revising the article, gave final approval of the version to be published, and agree to be accountable for all aspects of the work.

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