Current Understanding on Pain Mechanism in Migraine and Cluster Headache

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Abstract

Context: Migraine and cluster headache are undoubtedly painful conditions. The respective pathogenesis of these two conditions is incompletely understood. In both cases, the treatments used have largely been empirical and have relied to a much lesser extent on our understanding of the mechanisms causing pain. We hereby review the pain mechanisms in migraine and cluster headache, two of the commonest primary headache disorders.

Evidence Acquisition: A review of the English literature was conducted by searching PubMed for studies on pain mechanism in migraine and cluster headache. We entered [migraine] and [pain mechanism] in Pubmed and 488 articles were obtained. Articles were then included according to their relevance to the topic. Similarly, [cluster headache] and [pain mechanism] revealed 79 search results.

Results: There is evidence that the trigeminovascular system and neurogenic inflammation play important roles, together with certain areas of the brain, leading to these conditions being termed 'neurovascular headaches'. Functional imaging findings suggest a possible role of the dorsolateral pons in generating migraine attacks while the role of the hypothalamus in cluster headache is more firmly established.

Conclusions: Migraine and cluster headache have complex pathophysiologies. The exact mechanism causing pain in both conditions is incompletely understood and more research needs to be undertaken in this area.

Keywords: Migraine, Cluster Headache, Pain

1. Context

Migraine and cluster headaches are primary headache disorders. Migraine is typically characterized by moderate to severe attacks of unilateral pulsating headache, aggravated by routine activity and associated with nausea and/or photophobia and phonophobia (1). The two main sub-types of migraine are: migraine without aura and migraine with aura. Migraine with aura is associated with focal transient neurological deficit such as: visual, speech and/or language, sensory, motor, brainstem or retinal deficit (1). The widely accepted theory suggests that cortical spreading depression (CSD), a wave of neuronal hyperactivity followed by an area of cortical depression, accounts for the aura (2, 3). It was previously believed that migraine was associated with cerebral or meningeal vasodilatation. There are no human studies to prove this theory. Schoomman et al. conducted a 3 Tesla magnetic resonance angiography (3T MRA) study on nitroglycerine induced migraine attacks compared with placebo group. During migraine, blood vessel diameters were no different from baseline, nor between headache and non-headache sides (4).

Cluster headache (CH), the commonest of the trigeminal autonomic cephalalgias is one of the most painful conditions an individual can experience (5). CH attacks are characterised by recurrent, severe, unilateral pain which is orbital, periorbital, temporal, or any combination of these sites, lasting 15 - 180 minutes (1). The pain of cluster headache is associated with ipsilateral conjunctival injection, lacrimation, nasal congestion, rhinorrhoea, forehead and facial sweating, miosis, ptosis and/or eyelid oedema, and/or with restlessness or agitation (1). Female patients who suffer from CH attacks describe the pain as 'worse than childbirth' (6). The pain intensity is estimated to be 100 to 1000 times worse than migraine (7). CH has three cardinal features: the distribution of pain in the first division of the trigeminal nerve, the autonomic features and the stereotyped activation.

For a long time, cephalic pain has been considered separate from other forms of pain, and we have therefore witnessed these two research fields develop independently. More recently, it has become evident that several conditions causing prolonged or chronic pain are associated with chronic activation and sensitization of peripheral nociceptors and/or central nociceptive neurons in the dorsal

horn. Integrating these concepts into basic research on migraine pathophysiology, a new animal model for the enduring headache of migraine has been developed. However, the use of laboratory animals and in vitro models is hindered by the fact that no reliable biological markers for the measurement of cephalic pain exist. There is also doubt as to whether experimental animals (e.g. rats or cats) experience headache similar to humans. Therefore, pain studies in humans during migraine or cluster attacks using modern imaging techniques have offered new insights into the pathophysiology of headache. We discuss the pain mechanisms in migraine and cluster headache derived from our understanding of the processes involved in these two conditions and the areas of the brain involved.

2. Evidence Acquisition

An electronic search of PubMed for all publications on pain mechanism in migraine and cluster headache was performed. We used the key works: 'pain mechanism migraine', 'pain mechanism cluster headache', 'imaging migraine' and 'imaging cluster headache'. We searched articles published between 1980 and 2015. Relevant studies were included.

3. Results

3.1. The Trigeminovascular System and the Trigeminocervical Complex

The trigeminovascular system is the only sensory (afferent) innervation of the cerebral vessels but it also has an afferent function in pathophysiological settings (8). Its cell bodies are located in the trigeminal ganglion and they are bipolar. The peripheral fibers make a synaptic connection with the vessel, and other cranial structures, particularly the pain-producing large cranial vessels and dura mater (9, 10). These fibers are mainly found in the first (ophthalmic) division of the trigeminal nerve and have a widespread ramified network that may innervate several vessels ipsilaterally (11, 12). In both migraine and CH, pain occurs as a result of activation of the trigeminovascular system. This explains the distribution of pain in the ophthalmic division of the trigeminal nerve, which is more characteristic in CH attacks. It is unclear how the migraine attack is triggered but it is thought that CSD can activate the trigeminovascular system.

However, patients with migraine often experience cephalic pain outside the distribution of the ophthalmic division of the trigeminal nerve and sometimes pain at the back of the head, innervated by the greater occipital nerve (GON), can be the sole manifestation. This can be explained by the convergence of trigeminal and cervical afferents on to neurons in the trigeminocervical complex (TCC). The TCC is a part of brainstem and includes the caudal part of trigeminal nucleus caudalis and the dorsal hors of C1-C2 segments of spinal cord (13). Migraine attacks are a manifestation of central and peripheral sensitization. The central sensitization hypothesis suggests an altered processing sensory signal in the brainstem, where the neurons of trigemino-cervical (TCC) system become hyperexcitable (14, 15). Once the attack has begun, central neurons can propagate information about the pain process without the need for further external stimuli. The symptoms of central sensitization consist of reduced pain threshold and exaggerated pain response outside the original site of pain (16-18). The most common symptom of central sensitization is a phenomenon called allodynia (19). Cutaneous allodynia represents pain evoked by applying non-noxious stimuli to normal skin (19). Cutaneous allodynia could be evoked by activities such as: shaving, combing the hair, wearing glasses, contact lenses, earrings or tight clothing and might contribute to the transformation of episodic migraine to chronic migraine. Peripheral sensitization depends on the activation of peripheral nociceptors (20). The primary afferent nociceptive neurons express increased responsiveness to external thermal or mechanical stimuli at the site of inflammation or injury (21). Clinically, the peripheral sensitization is associated with the presence of throbbing headache and its aggravation during physical activities that increase the intracranial pressure such as bending over, breath-holding,coughing (21, 22). The sensitisation of the nociceptors that innervate the meninges may contribute to such intracranial hypersensitivity (23, 24). The first order neuron in the trigeminal ganglion receives input from the dural blood vessels and the signal is transmitted to the second-order neuron in the trigeminal brainstem nuclear system and therefore to the third-order neuron in the thalamus (25). The clinical expression of first-order-neuron sensitization is the throbbing pain that characterizes migraine attacks (25). When the sensitization spreads to the second-order neuron in the trigeminovascular system scalp sensitivity and allodynia occurs (25). The sensitization of third-order neuron in the thalamus is expressed clinically by extracranial hypersensitivity (24).

In CH, activation of the trigeminovascular system triggers autonomic manifestations through the trigeminal-autonomic reflex. The trigeminal nucleus caudalis has a functional brainstem connection with the superior salivatory nucleus (26) from which the parasympathetic efferent fibers of the facial nerve arise. Activation of parasympathetic fibers causes rhinorrhea, lacrimation, and nasal congestion while sympathetic malfunction results in ptosis, miosis.The excessive facial sweating present during CH

attacks is due to sympathetic over activity (27). Parasympathetic activation is mediated through the 7th nerve (28). The fibers originating from the superior salivatory nucleus synapse in the pterygopalatine ganglia. Blockade of the sphenopalantine ganglion is known to relieve the symptoms of CH. The postganglionic fibres innervate the cerebral blood vessels and the lacrimal and nasal glands. High flow-oxygen is an efficient abortive therapy for cluster headache (29). A study on rats conducted by Akerman et al. suggested that oxygen might act on parasympathetic outflow to the cranial vasculature and trigeminovascular system (30).

3.2. Neurogenic Inflammation

Neurogenic inflammation refers to a neurally mediated inflammatory response in meningeal tissue characterised by vasodilatation, leakage of plasma protein from blood vessels and mast cell degranulation. Neuropeptides such as calcitonin-gene related peptide (CGRP), substance P (SP) and vasoactive intestinal peptide (VIP) are released when the trigeminal fibres or trigeminal ganglion is activated (31, 32). This release of neuropeptides has been proposed as a pain mechanism in migraine and other primary headaches (33, 34). Histochemical studies on rats have revealed the presence of calcitonin gene related peptide (CGRP) and substance P in small nerve fibers that innervate the dura mater of the rat (35, 36). The nociceptive information is transmitted from meningeal blood vessels to the trigeminal nucleus caudalis through Aδ and C type nerve fibers arising from the trigeminal ganglion (37). The release of CGRP, a powerful vasodilator, from afferent terminals produces dilatation of the dural vessels and an increase in blood flow (35, 38). CGRP immunoreactive fibers are more abundant around the middle meningeal artery (MMA) whereas SP fibers are mostly found around main cerebral arteries (35). Another important mediator in migraine and other primary headaches is VIP. Elevated concentrations of CGRP, SP and VIP have been found in plasma samples during migraine attacks (39-41) and also in attacks of CH (28, 42-44). VIP derives from parasympathetic afferents (41) and raised levels in CH attacks are likely to reflect parasympathetic activation. CGRP is probably the most important of these mediators and this is evidenced by the successful treatment of migraine with antibodies against CGRP (45) and antagonists of its receptor (46, 47). Triptans appear to relieve pain by regulating CGRP levels (48).

CGRP mediates the release of histamine from mast cells and interacts with nitric oxide (NO) (49, 50). NO is another potent vasodilator found in different tissues including meningeal circulation (49, 51). Vasodilation resulting from the interaction between NO and CGRP release may

also play a role in the peripheral sensitization of perivascular afferent fibres (52). The infusion of nitrovasodilators can trigger CH attacks similar to spontaneous attacks, suggesting a role for NO in nociceptive processes (53). There is an obvious link between CGRP, vasodilatation and pain but its exact role during an attack is not yet very clear. While CGRP has a vasodilatory effect, SP and neurokinin A (NKA) increase vascular permeability in response to trigeminal nerve activation (31, 32). SP neurons display unique properties in that impulses may travel either orthodromically or antidromically in the various ramifications of the axons, and that the transmitter may be released both in the central and peripheral ends of the neuron (54). It has been hypothesized that activation of SP neurons in the ophthalmic and maxillary divisions can cause all the symptoms of an acute CH attack, and this could explain the improvement witnessed with blockade of the Gasserian or sphenopalatine ganglia (54).

3.3. Functional and Structural Brain Changes

Initial imaging in migraine focused on changes in cerebral blood flow during attacks. Studies by Olesen and Friberg (55) using single photon emission computed tomography (SPECT) revealed a focal reduction of cerebral blood flow for migraine attacks with aura, usually in the posterior parts of one hemisphere. Studies of cerebral blood flow in cluster headache are scarce and the majority has employed SPECT giving variable results. Some have reported an increase, some a decrease and others no differences in cortical blood flow (56). Modern functional imaging techniques have shed light on the regions of the brain involved in migraine and cluster headache, some being more specific to pain than others. These areas are discussed in more detail below.

3.4. Migraine

Evidence for the role of the brainstem as a generator has been gathering for some time. Weiller et al. using positron emission tomography (PET) imaging, found that following the administration of sumatriptan succinate in 9 patients during spontaneous migraine attacks, brainstem activation persisted even after sumatriptan had relieved the pain (57). The areas of maximum intensity were around the dorsal midbrain and dorsolateral pons (DLP) (57). A further PET study involving 5 patients who were not taking any migraine prophylaxis revealed significant activation of the dorsolateral pons during spontaneous migraine attacks, further reinforcing the idea that migraine is a subcortical disorder (58). There are proponents for the theory that the origin of migraine headache is in the periaqueductal gray (PAG). This notion gained popularity

when a clinical study in which implantation of stimulating electrodes in the PAG of 175 intractable pain patients resulted in short-lasting (12 patients) or long-lasting (3 patients) post-operative migraine-like headache (59). However, it should be noted that electrical stimulation of the PAG did not trigger a migraine in 174 of the 175 patients and that post-operative headache is usually observed following procedures involving craniectomy (60). Borsook and Burnstein make a good case against the brainstem as a migraine generator, arguing that it is inconceivable that the PAG, which is positioned to modulate pain at all spinal segment levels, would only generate cephalic pain but no pain in other body parts (61). In fact, DLP activation is not specific to migraine and is commonly seen in patients with neuropathic and visceral pain (62). DLP activation also can be present in response to bladder distension (63), changes in heart rate, plasma catecholamines during rectal distention (64) and sympathetic-nerve-related activity (65). These studies showed that the activation of the DLP is not specific to pain either.

Therefore, one of the challenges with PET studies is to differentiate between areas activated by general pain and areas that might be specific for migraine. One approach is to compare areas of activation and deactivation during a migraine attack and after effective abortive therapies. Areas activated during migraine attack are anticipated to be deactivated after triptan therapy whereas areas that generate pain remain active. In addition to the DLP, several other areas of the brain have shown activation on functional imaging. Afridi et al. detected activation in the thalamus, insula, anterior and posterior cingulate gyri, cerebellum, prefrontal cortex and temporal lobes (58). Other areas of increased activation include the red nucleus (66), substantia nigra (66) and hypthalamus (66) while areas of decreased activation include the somatosensory cortex (67), nucleus cuneiformis (61), caudate (68) and putamen (68). However, these regions again do not appear to be specific to migraine and most are generally activated in functional imaging studies on pain and collectively are known as the pain matrix. There is evidence for almost indistinguishable activation patterns in other pain conditions, such as low back pain, neuropathic pain, fibromyalgia, irritable bowel syndrome, and cardiac pain (69). It is therefore possible that the differences between somatic pain and migraine pain are not due to differences in central pain processing. In addition to functional alterations, structural changes have been noted in these areas. A Voxel-based morphometry and diffuse tensor imaging studies revealed gray matter volume reductions in the insula, motor/premotor cortex, prefrontal cortex, cingulate cortex, posterior parietal cortex, and orbitofrontal cortex (70), thickening of the somatosensory cortex (71) and increased gray matter density in the caudate (68).

Functional MRI studies have shown activation of the pulvinar in patients with migraine attacks with extra-cephalic allodynia (72). The authors concluded that sensitized posterior thalamic neurons mediate the spreading of multimodal allodynia and hyperalgesia beyond the locus of migraine headache (72). Medication overuse headache is a well-known problem in chronic migraine patients. Orbitofrontal cortex (OFC) hypofunction was a consistent finding in patients with medication overuse and after withdrawal of analgesics in a fludeoxyglucose F18 (FDG)-PET study conducted by Fumal et al. (73). The study aim was to test how medication overuse transforms episodic migraine into chronic migraine (73). The hypometabolic areas before withdrawal were the bilateral thalamus, orbitofrontal cortex (OFC), anterior cingulate gyrus, insula/ventral striatum and right inferior parietal lobule, while the cerebellar vermis was hypermetabolic (74). The orbitofrontal cortex was the only structure that did not recover after withdrawal of analgesics. The authors concluded that medication overuse is associated with reversible changes in the chronic pain processing structure, except OFC hypofunction that is seen in patients with drug addiction as well (73). More recently, functional imaging studies have shown activation of posterior/dorsal thalamic areas in spontaneous migraine (74). Animal studies on cats have identified trigeminothalamic projections in the posterior (Po), lateral posterior/dorsal (LP/LD) and ventral posteromedial (VPM) thalamic nuclei (75). Neuroanatomical studies showed that thalamo-cortical projections are defined by their thalamic nucleus of origin (74). Neurons in VPM project in primary, secondary sensory cortices and insula suggesting a role in the location, quality and intensity of pain (74). Contrariwise, thalamic neurons from Po, LP and LD nuclei project to brain areas such as the motor, auditory, olfactory, retrosplenial, ectorhinal, and visual cortices suggesting involvement in motor function, visual and auditory perception, spatial orientation, olfaction, difficulty focusing, transient amnesia, allodynia, common neurological symptoms during migraine (76).

3.5. Cluster Headache

Studies conducted by Kudrow et al. were the first to implicate the hypothalamus in the pathogenesis of CH with the demonstration of lower levels of testosterone during a bout (77). This was supported by studies showing observations of disordered circadian rhythm for cortisol, luteinizing hormone, growth hormone, and prolactin (78) and a suppressed nocturnal peak in melatonin is seen during the active phase of a CH (79). Neuroimaging further supports the role of the hypothalamus in CH. PET imaging studies in nitroglycerine-provocation or spontaneous CH have

found activation in the posterior hypothalamic matter (80). The activation pattern was not seen in patients with migraine or experimental ophthalmic division head pain, suggesting the involvement of hypothalamus in the pain process (80). Findings from PET studies were supported by Voxel-based morphometric MR imaging that has found significant structural differences in the hypothalamic posterior gray matter compared with controls (81). Sprenger et al. used PET with the opioidergic ligand [11C] diprenorphine on CH patients in and out of a bout and have found decreased tracer binding in the pineal gland, suggesting that the descending opioidergic mechanisms in the pineal gland and hypothalamus may play a role in the generation of cluster headache attacks (82). There is evidence of anatomical connections between the hypothalamus and the trigeminal nucleus (83) and between the hypothalamus and the superior salivatory nucleus (84). The importance of the superior salivatory nucleus activation has been shown in a novel model of TAC (30).

Imaging studies in CH have also implicated other brain areas that are generally associated with the pain matrix. The initial studies used single photon emission computed tomography (SPECT). Di Piero et al. conducted a Xe-133 SPECT study that showed differences in the cerebral blood flow in the contralateral primary sensorimotor and thalamic regions compared to control subjects (85). These findings suggested the involvement of central tonic pain in the pathogenenesis of CH. Hsieh et al. conducted a PET study on nitroglicerine-induced CH attacks that showed increased cerebral blood flow in the right caudal and rostrocaudal anterior cingulate cortex (ACC), temporopolar region, supplementary motor area, bilaterally in the primary motor and premotor areas, opercular region, insula/putamen, and lateral inferior frontal cortex (86). The same study showed reduction in cerebral blood flow bilaterally in the posterior-parietal cortex, occipito-temporal region and prefrontal cortex (86). The authors suggested that there is a preference for the non-dominant hemisphere in chronic pain processing (86). A FDG-PET study that measured the cerebral glucose metabolism during and outside the bout showed increased metabolism in the perigenual ACC, posterior cingulate cortex, the OFC, the nucleus accumbens, ventrolateral prefrontal cortex, dorsolateral prefrontal cortex and temporal cortex, and decreased metabolism in the cerebellopontine area (87). The same study revealed hypometabolism in the perigenual ACC, prefrontal and OFC in and out of the CH bout compared with normal group (87). The authors concluded that the hypomethabolism in and out of a bout in the PACC, a structure involved in the central descending opiatergic pain control system, may predispose to CH and to its recurrence (87).

4. Conclusions

Migraine and CH are neurovascular disorders with multiple processes and complex pathophysiologies. We have acquired better understanding of the role of the trigeminal vascular system in causing pain in these disorders. However, it is clear that other brain areas and trigeminothalamic projections all have a role to play in migraine. In CH, it is evident that activation of the hypothalamus is the key in generating attacks. Our understanding of the pain mechanisms of these two conditions continues to improve and is crucial for the development of novel treatments. Research in this field, using animal models and the ever-advancing techniques of functional imaging, will undeniably assist in the quest for specific drugs for these painful disorders.

Footnotes

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