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Invited review

Glial involvement in trigeminal central sensitization[1]

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Key words

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Abstract

Recent studies have indicated that trigeminal neurons exhibit central sensitization, an increase in the excitability of neurons within the central nervous system to the extent that a normally innocuous stimulus begins to produce pain after inflammation or injury, and that glial activities play a vital role in this central sensitization. The involvement of glial cells in trigeminal central sensitization contains multiple mechanisms, including interaction with glutamatergic and purinergic receptors. A better understanding of the trigeminal central sensitization mediated by glial cells will help to find potential therapeutic targets and lead to developing new analgesics for orofacial-specific pain with higher efficiency and fewer side-effects.

Introduction

Central sensitization refers to the increased synaptic efficiency established in nociceptive neurons in the dorsal horn of the spinal cord following intense peripheral noxious stimuli, tissue injury, or nerve damage to the extent that a normally innocuous stimulus begins to produce pain and thereby plays a major role in the generation of acute postoperative and post-traumatic pain, migraine, and neuropathic pain[1]. There is accumulating evidence that glia cells (mainly astrocytes and microglia) in the central nervous system are activated by inflammation or peripheral nerve injury and are involved in spinal nociceptive transmission and central sensitization[2-5]. Astrocytes and microglia participate in neuronal sensitization, not only via indirect mechanisms (ie the release of cytokines and various neuroligands), but also more directly via the release of glutamate and/or by evoking changes in synaptic ion homeostasis[6,7].

Trigeminal sensory nuclei mainly consist of the principal subnucleus (Vp) and the spinal trigeminal subnuclei, including oralis (Vo), interpolaris (Vi), caudalis (Vc) nuclei, and the mesencephalic trigeminal subnucleus. The oral nociceptive signal is primarily processed in Vp, Vo, and Vi, and secondarily processed in Vc. In contrast, the facial nociceptive signal is primarily processed in Vc nucleus[8]. Because of its many anatomical and functional similarities with the spinal dorsal horn, Vc has been termed the "medullary dorsal horn"[8-12]. However, the neurochemical and neurophysiological changes induced by injury to nerves of the trigeminal system are clearly distinct from those seen following lesions of other peripheral nerves[13]. Recently, a series of experiments were undertaken to investigate the glial mechanisms in trigeminal central sensitization, which will help to find potential therapeutic targets and lead to developing new analgesics for orofacial-specific pain with higher efficiency and fewer side-effects.

Glial activation in trigeminal central sensitization

Increasing evidence indicates that central sensitization could be induced in trigeminal nociceptive neurons, and the central sensitization occurring in trigeminal nociceptive pathways shows more robust neuronal hyperexcitability following deep tissue stimulation than cutaneous stimulation[14]. Our studies have identified nociceptive neurons in Vc, and have demonstrated that the small-fiber excitant and inflammatory irritant mustard oil (MO) applied to orofacial regions produces long-lasting central sensitization in Vc, as reflected in neuroplastic changes, such as increases in neuronal spontaneous activity, receptive field size, responses to suprathreshold

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stimuli, and a decrease in the activation threshold[15-18]. Piao *et al* found that tactile hypersensitivity was significantly increased at d 1 and lasted for 28 d, and was gradually reduced, finally returned to the basal level by 60 d after inferior alveolar nerve and mental nerve transection (IAMNT)[19]. Similarly, after the surgical removal of a lower impacted third molar, intraoral repetitive pinprick and electrical stimulation also induced central sensitization indicated by significantly increased pain intensity, and this phenomenon lasted for at least 1 week[20]. These studies pointed out that the central sensitization occurred in trigeminal neurons under pathological conditions and appeared to play an important role in the transition from acute to chronic orofacial pain. It is suggested that trigeminal central sensitization involves an increase in the excitability of Vc neurons brought about by a series of events, including neuronal depolarization; removal of the voltage-dependent magnesium block of the *N*-methyl-*D*-aspartate (NMDA) receptor; release of calcium from intracellular stores; phosphorylation of the NMDA, alpha amino-3-hydroxy-5-methyl-4-isoxazole-propionate (AMPA), and neurokinin 1 receptors via the activation of protein kinases; a change in the neuron's excitability; and an increase in synaptic strength[14]. The trigeminal central sensitization proposes that the altered processing of sensory input in the brainstem, principally Vc, could account for, at least in part, many of the temporal and symptomatic features of migraine, its poor response to triptan therapy when such treatment is initiated hours after the onset of pain, as well as the role of glutamate in migraine[21,22].

Recent studies have demonstrated that the trigeminal central sensitization involves glial activation. The presence of glial fibrillary acidic protein (GFAP)/substance P (SP)- or GFAP/calcitonin gene-related peptide (CGRP)-positive reactions by double-labeling immunofluorescence was clarified, and the morphological interrelationship between the astrocytes and nerve endings by the double-labeling electron microscopic immunohistochemistry in laminae I and II of Vc was demonstrated[23]. In the model of trigeminal central sensitization induced by the application of MO to the rat's tooth pulp, we found that the intrathecal application of SB203580 [an inhibitor of p38 mitogen-activated protein kinase (p38MAPK)] or fluoroacetate (FA; an inhibitor of the astroglial metabolic enzyme aconitase) markedly attenuated the MO-induced increases in pinch receptive field size and responses to noxious stimuli, and the decrease in the activation threshold[18]. Furthermore, the MO-induced central sensitization can be significantly attenuated by continuous intrathecal superfusion of methionine sulfoximine (MSO), an inhibitor of the astroglial glutamine synthetase that is involved in the glutamate-glutamine shuttle. The simultaneous superfusion of MSO and glutamine restored the irritant-induced central sensitization[17]. In a subcutaneous injection of formalin in a mystacial vibrissae experiment, the formalin injection significantly increased the Cx32/Cx43 heterotypic gap junctions on junction areas between astrocytes and neurons within Vc and nociceptive behavior, while the administration of carbenoxolone (CBX; a gap junction blocker) or fluorocitrate (FCA; an inhibitor of the astroglial metabolic enzyme aconitase) into the cerebellomedullary cistern significantly reduced the nociceptive behavior and scratching–cumulative time. CBX and FCA also decreased the number of Fos/neuronal nuclei (NeuN)-immunoreactive (-IR) neurons or obviously attenuated the expression of Fos/NeuN-IR neurons and Fos/GFAP-IR astrocytes in the Vc, respectively[24]. It was found that microglial activation, primarily observed in the superficial laminae of Vc, continued 2 weeks after IAMNT, while astrocytic activation was delayed compared to that of microglia. Minocycline, an inhibitor of microglial activation, reduced microglial activation, but inhibited p38MAPK activation in microglia and significantly attenuated the development of pain hypersensitivity in this model[19]. These results suggest that glial activation and metabolic processes in the trigeminal system play an important role in trigeminal central sensitization, and therefore, in the development of inflammatory and neuropathic pain.

Mechanism of glia activation in trigeminal central sensitization

The glial mechanisms in trigeminal central sensitization most likely involve their interactions with the glutamatergic receptor, which is a critical process in central sensitization. It has been demonstrated that astrocytes may directly influence the state of presynaptic terminals through the activation of presynaptic mGlutRs, presynaptic and/or extrasynaptic NMDA receptors by increasing the probability of neurotransmitter release from nerve terminals and modulating synaptic transmission between cultured hippocampal neurons[25-28]. Our results indicated that pretreatment with the NMDA receptor antagonist MK-801 followed by MO application to the tooth pulp of rats significantly reduced or abolished these MO-induced neuroplastic changes in nociceptive neurons[29], and that disturbing the astrocyte glutamate–glutamine shuttle by the inhibitor of the astroglial enzyme glutamine synthetase or inhibiting the astrocyte metabolic enzyme aconitase by FA also abolished the MO-induced central sensitization[17,18]. Furthermore, the involvement of NMDA receptors may, at least in part, be related with the phosphorylation medicated by interleukin (IL)-1 receptor signaling. In

response to masseter inflammation, there was an upregulation of GFAP and IL-1, a prototype pro-inflammatory cytokine, in astrocytes of the region of the trigeminal nucleus specifically related to the processing of deep orofacial input. The activated astrocytes exhibited hypertrophy and an increased level of connexin 43, an astrocyte gap junction protein. Local anesthesia of the masseter nerve prevented the increases in GFAP and IL-1β after inflammation, while substance P, a prototype neurotransmitter of primary afferents, induced similar increases in GFAP and IL-1β, which was blocked by a nitric oxide synthase inhibitor $N^{(G)}$-nitro-*L*-arginine methyl ester. An injection of an IL-1 receptor antagonist and FCA attenuated hyperalgesia and NMDA receptor phosphorylation after inflammation. The *in vitro* application of IL-1β induced NR1 NMDA receptor phosphorylation, which was blocked by an IL-1 receptor antagonist, a protein kinase C inhibitor, an inositol trisphosphate (IP_3) receptor inhibitor, and inhibitors of phospholipase C and phospholipase A2[30]. Similarly, it was found that inflammation of the whisker pad could produce hypersensitivity, increase the trigeminal ganglion astrocyte activation, and induce depolarization in trigeminal ganglion neurons by IL-1. These effects could be abolished by the application of an IL-1 receptor antagonist[31]. Our study indicated that the intrathecal application of the p38MAPK inhibitor attenuated the trigeminal central sensitization induced by MO[18]. Furthermore, pretreatment with a p38MAPK inhibitor attenuated not only thermal hyperalgesia and mechanical allodynia, but also the NMDA-evoked release of prostaglandin E2 (PGE2)[32-35]. It was found that microglial produced TNFα and enhanced synaptic efficiency by increasing the surface expression of AMPA receptors while preventing the actions of endogenous tumor necrosis factor (TNFα)[36]. These results suggest that the activation of p38MAPK in microglia play a role in trigeminal central sensitization via interaction with glutamatergic receptors.

Furthermore, the involvement of glia in trigeminal central sensitization may be related with the P2 purinergic activation. It has been reported that ATP stimulates brain-derived neurotrophic factor (BDNF) release from microglia, which causes a depolarizing shift in the anion reversal potential in spinal lamina I, while blocking the neuron–microglia signaling reverses the allodynia[37]. Our studies documented that the P2X receptor antagonist attenuated the central sensitization induced in Vc nociceptive neurons by MO, and that P2X receptors in Vc modulate central sensitization in Vo[16,38]. FA pretreatment produced a substantial reduction in ATP in glial cells, which can be prevented by simultaneous application with FA of the astroglial metabolic substrate isocitrate[39]. It has been indicated that glutamate and norepinephrine stimulate ATP release from astrocytes via most likely exocytosis to increase postsynaptic efficiency[40,41], and that the efficiency increases, which most likely results from an insertion of AMPA receptors, is secondary to the activation of P2X receptors, the increase in postsynaptic calcium, and the activation of phosphatidylinositol 3-kinase[41]. In primary mouse neuron–glia trigeminal cultures, the presence of functional neuronal P2X, as well as P2Y receptors on both neurons and glia were characterized. Treatment with pro-inflammatory agent bradykinin resulted in the potentiation of algogenic P2X receptor-mediated calcium responses followed by their downregulation at 24 h, while P2Y receptor responses in satellite glia were instead upregulated[42], suggesting a complex modulation of P2 receptors in trigeminal pain signalling. These further imply that the involvement of purinergic receptors in trigeminal central sensitization is also related with calcium signalling, which is pending further study.

Additionally, the glial activities may mediate the sensitization by controlling the activities of blood vessel in the microenvironment and this control may involve purinergic and dopaminergic activities. It was found that photolysis of caged Ca^{2+} in astrocytic endfeet ensheathing the vessel wall was associated with an 18% increase in arterial cross-section area that corresponded to a 37% increase in blood flow and that both indomethacin and the cyclooxygenase-1 inhibitor SC-560 blocked the photolysis-induced hyperemia[43]. In addition, it has been determined that dopamine receptors were present in the rat trigeminocervical complex and dopamine applied microiontophoretically inhibited *L*-glutamate-evoked cell firing in the trigeminocervical complex dose-dependently and inhibited the activation of trigemino-cervical neurons in response to middle meningeal artery stimulation, suggesting that central dopamine-containing neurons may play a role in modulating trigeminovascular nociception and these neurons offer an important target that will expand our understanding of migraine and may offer new directions for therapy[44]. These observations implicate astrocytes in the control of local microcirculation and suggest that one of their physiological roles is to mediate vasodilation in response to increased neural activity during sensitization.

Prospect

It has been well established that spinal microglia and astrocytes play different roles in the development and maintenance of central sensitization. However, there is only 1

paper[19] indicating that inferior alveolar nerve and mental nerve transection activates microglia and astrocytes maximally at 3 and 7 d, respectively, after transection, which implies that similar mechanisms may exist in the trigeminal system. However, there is not enough evidence reported to support this hypothesis, so further study is necessary. Following the elucidation of the glial mechanism in trigeminal central sensitization, the pain field would benefit more from this approach to make potential therapeutic agents, such as IL-1β blockers, glutamate receptor antagonists, and p38MAPK inhibitors for the prevention of trigeminal pain. However, clinical studies reporting the side-effects of some agents also suggest that the need for further studies to elucidate the complicated mechanism in trigeminal system is very necessary.

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