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Understanding Migraine: Epidemiology, EEG Abnormalities, and the Potential of Neurofeedback Training

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Abstract

Introduction. Migraine is a prevalent neurovascular disorder with a significant impact on individuals' quality of life. In this paper, we focus particularly on electroencephalogram (EEG) studies, and the ability of that modality to detect abnormalities in brain waves and provide insights into migraine pathophysiology. Neurofeedback training (NFT) as a potential therapeutic approach for migraine management is also explored. **Methods**. The manuscript provides a review of relevant literature on the epidemiology, classification, pathophysiology, and measurement techniques related to migraine. **Results**. Epidemiological studies highlight the high prevalence of migraine. EEG studies demonstrate delta and beta wave variations in people who experience migraine. Functional connectivity studies using EEG and functional magnetic resonance imaging (fMRI) suggest involvement of specific brain regions, including the prefrontal cortex, anterior cingulate cortex, amygdala, and insular cortex, in migraine pathophysiology. NFT studies indicate promising outcomes in reducing migraine frequency and severity. **Conclusion**. Migraine is a complex disorder with multiple subtypes and triggers. Advances in understanding its pathophysiology suggest the involvement of cortical and brainstem mechanisms, as well as cortical spreading depression. EEG abnormalities provide valuable insights into the neurobiological dysfunctions associated with migraine. NFT shows promise as a noninvasive and personalized treatment option. Future research should further investigate the mechanisms underlying EEG abnormalities and continue to develop effective interventions for migraine management.

Keywords: migraine; electroencephalogram (EEG); neurofeedback training (NFT); functional connectivity; brain waves; EEG abnormalities

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Epidemiology of Migraine

Migraine is a neurovascular disorder and a leading cause of disability, affecting more than one billion people worldwide (Ashina et al., 2021). The percentage of Americans experiencing migraine is estimated at about 15% (Peters, 2019). Head pain or headache was cited as the fifth leading cause of emergency department (ED) visits in the United States (Smitherman et al., 2013). Sudden or severe headache accounts for 3.5 million ED visits per year in the United States (Yang et al., 2022). Migraine significantly impairs many individuals' quality of life and ability to participate in social, work, and family activities (Peters, 2019).

Age, gender, and ethnicity are nonmodifiable risk factors associated with migraine occurrence. As opposed to most other chronic conditions, migraine tends to affect relatively healthy individuals that are young or middle-aged. Migraine prevalence was found to be highest among those between 18 to 44 and lower as people age (Peters, 2019). Women are more prone to self-reporting migraine or severe headache. In 2015, the rates were highest among American Indians and Alaskan Natives, when compared with Whites, Hispanics, or Blacks. High prevalence was also found among people who are unemployed, individuals with family income below the poverty line, older adults, and people with disabilities (Burch et al., 2018). Migraine is linked to increased risk for other physical and psychological comorbidities, and this risk increases with headache frequency and severity. Migraine and severe headache are a major public health issue.

Introduction to Migraine

Migraine is a complex neurological disorder characterized by episodes of moderate to severe headache. It is mostly unilateral and tends to be associated with light and sound sensitivity, in addition to nausea (Pescador Ruschel & De Jesus, 2022). Migraine has a strong genetic influence, but a pattern of inheritance has yet to be identified. It is uncertain which genes and loci are implicated in migraine pathogenesis (Pescador Ruschel & De Jesus, 2022). The complex genetic component likely interacts with environmental factors to influence susceptibility and symptoms of the disease in affected individuals.

Migraine can be subdivided into multiple classifications. The first is migraine without aura, which is the most prevalent type. These occur in about 75% of migraine cases, consisting of a recurrent headache attack lasting a few hours or days (Pescador Ruschel & De Jesus, 2022). Aura is a group of sensory, motor, and speech symptoms that tend to signal warnings that a migraine attack is about to occur (Shankar Kikkeri & Nagalli, 2022). These symptoms are reversible and include seeing bright lights or blind spots, numbing, or tingling of the skin, changing of speech, smell, or taste, and ringing of the ears (Pescador Ruschel & De Jesus, 2022). Migraine with aura consists of recurrent and fully reversible attacks lasting minutes, with multiple unilateral symptoms (Shankar Kikkeri & Nagalli, 2022). Chronic migraine is another subtype, characterized by a headache that occurs at least 8 or more days in a month for more than 3 months (Pescador Ruschel & De Jesus, 2022).

Triggers are common in the development of migraine headaches. Stress is the most probable factor, followed by hormonal changes in women, skipped meals, lack of sleep, odors, and exposure to light (Park et al., 2016).

For a long time, migraine was considered to be a vascular disorder. The throbbing, pulsating quality associated with headaches was thought to be caused by mechanical changes in vessels (Mason & Russo, 2018). Aura was said to be produced by vasoconstriction and headache by vasodilation (Pescador Ruschel & De Jesus, 2022). This theory is no longer considered viable. Currently, a new explanation for the pathophysiology of migraine is being offered, which suggests that multiple primary neuronal impairments lead to the intracranial and extracranial changes that produce migraines (Pescador Ruschel & De Jesus, 2022).

One postulated mechanism is cortical spreading depression (CSD), an electrophysiological phenomenon characterized by a slowly propagating wave of altered brain activity, involving dramatic changes in neuronal, vascular, and glial function (Charles & Baca, 2013). CSD is now widely thought to be the mechanism by which migraine with aura occurs (Cozzolino et al., 2018). In migraine without aura, it is hypothesized that CSD occurs in areas like the cerebellum, where depolarization is not consciously perceived (Takano & Nedergaard, 2009).

There is significant imaging and clinical evidence for changes in cortical activity among migraineurs (people who experience migraine; Charles & Brennan, 2010). For instance, visual changes tied to migraine aura likely rise from altered function of the occipital lobe, corresponding with the primary visual cortex. Migraineurs may additionally undergo cortical sensory, language, motor, or other cognitive dysfunction (Dai et al., 2021). There is also strong support for the brainstem's role in the pathophysiology of migraine (Goadsby et al., 2017). Autonomic symptoms, along with nausea and vertigo, may be due to changes in the signaling of the brainstem. The brainstem is a key region that receives input from the trigeminal nerve, which carries pain signals from the head and face. During a migraine attack, there is evidence to suggest that the brainstem's pain-modulating circuits may malfunction, leading to an amplification of pain signals and a decreased ability to inhibit pain (Charles & Brennan, 2010). This dysfunction may contribute to the severe and debilitating headache experienced in migraines.

The sequence of activation of different brain areas in migraine continues to remain uncertain. One hypothesis is that cortical activation precedes brainstem activation, due to the typical occurrence of migraine aura before migraine headache (Charles & Brennan, 2010). Brainstem activation has also been shown to evoke changes in cortical blood flow, which raises the possibility for the opposite sequence. It is also possible for both brain regions to be activated at the same time. This is supported by clinical observations in people who experience symptoms without any clearly defined order. Regardless of the order of activation, there is significant evidence to suggest that cortical and brainstem mechanisms are involved in the development of different kinds of migraine (Charles & Brennan, 2010).

Measurement Techniques

Multiple approaches have been taken to explore the various aspects of migraine pathophysiology, including musculoskeletal impairments, neuroendocrine signaling, and neurological measurements. Physical examination tests focusing on the cervical musculoskeletal system have been used to differentiate between migraine, secondary headaches, and asymptomatic individuals (Anarte-Lazo et al., 2021). These tests encompassed measures such as range of motion, muscular strength and endurance, tenderness palpation, proprioceptive measures, and balance assessment. Such examinations can help rule out other underlying conditions that mimic migraine symptoms.

Neuroendocrine signaling has also been investigated in relation to migraine pathophysiology. Insulin, glucagon, and leptin, which play roles in appetite and glucose regulation, have been found to influence trigeminovascular nociceptive processing and neural activity in the trigeminocervical complex and hypothalamus. These peptides have the potential to modulate specific neural networks relevant to migraine and contribute to the development of migraine attacks (Goadsby et al., 2017).

Functional magnetic resonance imaging (fMRI) has frequently been used to investigate the neural mechanisms of migraine (Shi et al., 2020). Resting-state fMRI is used to explore the functional connectivity between brain regions. This is measured by fluctuations of blood-oxygenation-level-dependent (BOLD) signals (Chong et al., 2019). Previous research has heavily focused on using fMRI measurements to show that migraine and headache disorders are associated with abnormal functional connectivity of many brain regions. These include regions associated with pain processing, along with many core resting-state networks, such as attention, salience, sensorimotor, executive, visual, limbic, and default mode networks (Chong et al., 2019). Functional MRI studies have so far enhanced our understanding of hypersensitivities in migraine, including the identification of brain regions and networks which are associated with abnormal processing of sensory stimuli. This kind of sensory processing is a key feature of migraine, in which individuals are exposed to olfactory, visual, and auditory stimuli that trigger migraine attacks. Most fMRI studies are focused on the interictal phase, which is the period between migraine attacks. These studies have shown consistently abnormal brain responses in the interictal phase to sensory stimuli, absence of normal habituating response, and atypical functional connectivity of the main sensory processing regions among migraineurs (Schwedt et al., 2015). Since migraine is mainly a disorder of brain function, fMRI studies continue to remain useful in studying the underlying mechanisms of migraine. The remainder of this review will focus on another promising method of measuring brain functional connectivity in headache disorders, specifically the use of electroencephalograms (EEGs).

Historically, EEG changes have been a subject of interest in studying migraineurs, with varying reports of definitively abnormal EEG rhythms (Sand, 1991). While some studies have indicated normal EEG findings in individuals with migraines, others have observed slight excesses of different EEG rhythms. These discrepancies in findings could be attributed to differences in patient populations, methodology, and the timing of EEG recordings in relation to migraine attacks. Modern approaches utilizing EEG frequency analysis and topographic brain mapping have proven valuable in exploring these abnormalities (Sand, 1991).

During visual aura, specific EEG changes have been noted in some migraine cases, including slow-wave activity across all cortical areas and a decrease in background activity amplitude (Bjørk et al., 2009) Nonetheless, it is essential to acknowledge that not all migraineurs experience these EEG abnormalities during aura, and normal EEGs have been reported in other cases (Bjørk et al., 2009). Among the most consistent EEG abnormalities recorded in migraineurs are the presence of unilateral or bilateral delta activity during attacks of migraine with disturbed consciousness and hemiplegic migraine (Sand, 1991). This abnormal delta activity, characterized by slow waves in the EEG, may offer valuable insights into the underlying mechanisms of these specific types of migraines. Additionally, EEG frequency analysis studies have consistently demonstrated significant and consistent variability in delta and beta waves among migraineurs (Sand, 1991). Delta waves, associated with slow-wave sleep, have been linked to abnormal brain activity and neuronal synchronization in migraineurs. Meanwhile, the variability observed in beta waves, which are associated with alertness and active cognition, potentially reflects changes in brain excitability and sensory processing in individuals with migraines.

While EEGs may not be the most specific tool for diagnosing migraines, they serve as a valuable platform for studying brain wave patterns and abnormalities that can enhance our understanding of migraine pathophysiology and explore potential treatment options, particularly for chronic migraine and headache patients (de Tommaso, 2019). EEG recordings can help identify abnormal brain wave patterns, such as slow waves, sharp waves, and excessive high-frequency beta activity, which may be associated with migraines. By analyzing EEG data, researchers can gain insights into the functional connectivity and network abnormalities in the brain regions involved in migraine. In addition, it is much more accessible, portable, and requires fewer resources than MRI. In line with observed EEG abnormalities, EEG-based neurofeedback training (NFT) has emerged as a potential therapeutic approach to modulate brain activity and potentially reduce the frequency and severity of migraines (Martic-Biocina et al., 2017). This approach aims to target and regulate specific abnormal brain wave patterns associated with migraines, providing a means for people to learn to self-regulate brain activity and potentially alleviate symptoms.

Experimental Studies

EEG changes have frequently been noted among migraineurs. Such changes include generalized slowing of activity, along with sharp and spike waves (Bjørk et al., 2009). Despite the practically equal number of reports indicating normal and abnormal findings, EEG frequency analyses in common and classic migraine patients continue to receive more and more attention (Bjørk et al., 2009). Neufeld et al. (1991) studied the EEGs of otherwise healthy participants, 18–28 years of age. This was divided among patients with common migraine, classic migraine, and age-matched controls. EEG findings in all three groups indicated mild nonspecific slowing (Neufeld et al., 1991). Sownthariya and Anandan (2017) conducted another study to investigate abnormalities in the electroencephalography of migraineurs. Participants were 100 migraineurs, 10–40 years of age. About 29% of those studied were found to have EEG abnormalities. When comparing migraine with aura and migraine without aura, those exhibiting the former had a higher percentage (~15%) of EEG abnormalities. Migraine with aura showed changes in the frontal and occipital regions. Migraine without aura patients showed changes in the frontal, occipital, and temporal regions. The most common abnormality was slow waves followed by sharp wave changes (Sownthariya & Anandan, 2017). It also showed a higher prevalence of migraine without aura, compared to migraine with aura (Sownthariya & Anandan, 2017).

Rho et al. (2020) conducted a retrospective analysis which reviewed the medical records of 259 pediatric patients with headaches that underwent EEGs over a time span of 3 years. Their methods involved comparing the EEG abnormalities by type of headache and characteristics of wave findings, along with a comparison of the clinical observations between those with normal versus abnormal EEGs. EEG was recorded when the physical examination or medical history of a patient revealed signs of a suspected seizure, such as visual or brainstem auras, continued headaches, or lack of response to medical treatment. Those with history of epilepsy, seizures, significant abnormal brain imaging, or cognitive impairment were excluded from the study. Of the 259 participants, only about 12% showed EEG abnormalities. The Pediatric Migraine Disability Assessment score, used in this study to evaluate the severity of headaches, was significantly higher in the abnormal EEG group, when compared to the normal group. Migraines with aura were found to exhibit more EEG abnormalities than the other types of headaches (including migraine without aura, probable migraine, tension-type headache, and probable tension-type headache). These findings suggest that people with migraines with aura might have overlapping pathophysiologic mechanisms with other neurologic disorders, such as epilepsy. The authors indicate that these people may benefit from electroencephalography in distinguishing between different headache types (Rho et al., 2020).

Exploring Brain Localizations and Connectivity

The specific brain areas that account for the functional abnormality of migraine have yet to be fully elucidated (Rho et al., 2020). Rather than a replacement for traditional fMRIs, EEGs can be used as a supplemental tool in understanding which areas are most involved in the pathophysiology of migraine.

Frequent migraine attacks may be associated with abnormalities in certain brain regions involved in pain processing. Increased functional connectivity has been cited in cerebral areas such as the prefrontal cortex and right rostral anterior cingulate cortex (Ong et al., 2019). Researchers cited stronger connections between the medial prefrontal cortex and both the posterior cingulate cortex and bilateral insula (Taylor et al., 2009).

The anterior cingulate cortex (ACC) is a key structure in the pain processing network. It is involved in descending pain modulation, emotional dimensions of pain, and attention to pain, and it has been implicated in the functional abnormalities of pain-related disorders, including severe headaches and migraine (Edes et al., 2019). A pilot study published in 2019 found that increased sensitivity of the right pregenual ACC (pgACC) to increased serotonin levels in the brain is linked to recurring headaches, along with increased stress sensitivity and emotional aspects of pain. This suggests that pgACC activation might increase during migraine attacks, which may contribute to the suffering element of pain associated with migraine (Edes et al., 2019).

The amygdala is involved in nociceptive processing and emotional responses. Researchers have suggested that functional or structural abnormalities here might contribute to the worsening of pain and mood that occurs in those who suffer from migraine (Huang et al., 2021). They concluded that people with migraine without aura showed decreased connectivity from right amygdala to the right and left superior temporal gyrus and the right precentral gyrus. Effective connectivity between these regions is associated with lesser disease duration (Huang et al., 2021). This might explain the amygdala's role in pain modulation, processing, and duration of migraine. The prefrontal cortex is another region that is important in pain modulation and has been implicated in migraine disorders (Ong et al., 2019).

Another study showed increased functional connectivity between the insular cortex and the default mode network, along with frontoparietal regions (Yuan et al., 2012). The authors remarked on the need for reproducibility of these findings in additional studies. Only by doing so, can these studies be placed in a broader context of understanding functional abnormalities that contribute to migraine and other trigeminal pain disorders.

Neurofeedback Training

Biomedical treatments are not always fully effective in managing the symptoms of chronic pain, including migraine. NFT is one therapy method of targeting the physiological brain abnormalities associated with pain processing (Marzbani et al., 2016). NFT is a noninvasive therapy that aids in regulating brain activity (Marzbani et al., 2016). It is a form of biofeedback that provides users with real-time information regarding their brain activity, allowing them to learn ways to directly change this activity and improve their experience of health and comfort (Roy et al., 2020). The user starts by wearing small electrodes on the scalp that monitor brain activity during the training session. Generally, users will engage by playing a game or watching a video. Measured changes in brain activity are fed back to the user, and every time the targeted brain regions exhibit EEG abnormalities, the game or video will stop. Through this process, the brain gradually learns to change its electrical activity to reduce interruptions and obtain a more cohesive perceptual experience. The objective is to cancel out specific functional abnormalities as the brain recruits new resources, ultimately reducing associated disturbances, such as those involved in pain processing (Roy et al., 2020).

NFT can be performed either by using brain activity measured through EEG or fMRI (Marzbani et al., 2016). Empirical studies have utilized both EEG and fMRI technology to examine the use of NFT in relation to pain. Most of these studies used EEG-based neurofeedback training, due to its lower cost and easier accessibility. A wide range of NFT methods have been used to increase, decrease, or moderate brain activity in specific areas associated with pain (Roy et al., 2020). In a recent systematic review, Roy et al. found an overall positive outcome for this approach (Roy et al. 2020). They concluded that NFT has the potential for reducing pain and improving other behavioral and cognitive outcomes in individuals experiencing chronic pain (Roy et al., 2020). More research is needed however to recommend protocols or methods of therapy that may be most effective.

Martic-Biocina et al. (2017) reported a successful case of biofeedback training, including neurofeedback, in treating a 25-year-old woman with painful migraines. The treatment consisted of 25 sessions using three forms of biofeedback therapy. Administered protocols consisted of the following: inhibition of theta waves (4–9 Hz), enhancement of low beta waves (12–15 Hz), and inhibition of high beta waves (22–30 Hz). The woman experienced a gradual reduction in pain severity and migraine frequency over 4 months, and she no longer required analgesics (Martic-Biocina et al., 2017). While this case highlights the positive potential of biofeedback therapies for migraine, further research with larger sample sizes and different protocols is needed to establish the best treatment method (Martic-Biocina et al., 2017).

Walker et al. (2011) conducted a study comparing NFT and drug therapy outcomes in 71 people with recurrent migraine without aura. Upon quantitative electroencephalogram (qEEG) screening procedure, all results showed excessive high-frequency beta activity in one to four cortical regions (Walker, 2011). About a third of the participants chose to undergo drug therapy, whereas the remaining selected to participate in NFT. NFT consisted of decreasing high-frequency beta activity in the 21–30 Hz range and increasing 10 Hz activity, over five sessions for each affected region. Among the NFT group, 54% experienced complete cessation of migraine headaches. Thirty-nine percent experienced a decrease in migraine frequency of more than 50%. Four percent experienced a decrease in headache frequency of more than 50%. Only one person did not experience a reduction in migraine frequency. Meanwhile, in those who chose drug therapy, 65% experienced no change in migraine frequency. Twenty percent of this group experienced a reduction of less than 50%, and 8% reported a reduction of greater than 50%. This study seems to provide promise for the efficacy of qEEG-guided neurofeedback in reducing or abolishing headache frequency in those with recurring migraine. However, one alternative explanation is that the self-selecting, nonrandomized allocation to groups confounds the results, whereby those who chose the "experimental" treatment were more sensitive to placebo effects.

Conclusion and Future Directions

In conclusion, migraine is a complex neurological disorder with a significant impact on individuals worldwide. While its exact pathophysiology remains unclear, advancements in research have shed light on various aspects of the condition. Epidemiological studies have revealed the high prevalence of migraine, particularly among specific demographics. This highlights the need for further investigation into understanding the underlying mechanisms and developing effective interventions.

In terms of measurement, EEG has emerged as a valuable tool in studying migraine. EEG abnormalities, such as delta and beta wave variations, have been observed in migraineurs. These findings provide insights into the neurological dysfunctions associated with migraine, particularly during attacks and specific migraine subtypes. Additionally, the identification of brain areas, including the cortical, brainstem, and sensory processing regions has enhanced our understanding of the neurobiological basis of migraine.

Furthermore, NFT shows promise as a potential intervention for migraine. By targeting abnormal brain activity through real-time feedback, neurofeedback has demonstrated positive outcomes in reducing migraine frequency and severity. This approach holds potential for personalized and noninvasive treatment options, emphasizing the importance of further research in this area.

To advance our knowledge of migraine, future studies should focus on investigating the specific mechanisms underlying the observed EEG abnormalities and their relationship to clinical manifestations. Additionally, exploring the potential of neuroendocrine function and musculoskeletal assessments could provide a comprehensive understanding of migraine's multifaceted nature.

In summary, the integration of epidemiological data, EEG analysis, and the identification of key brain areas in migraine research presents a valuable framework for unraveling the pathophysiology of this complex disorder. With ongoing advancements in technology and treatment modalities like NFT, there is optimism for improving the management and quality of life for individuals affected by migraine.

Author Disclosure
M. Keane is Director of the Actualise Psychological Services Clinic which provides NFT services. L. Abdurrahman is a Medical Student who served an internship at the Actualise Clinic.

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