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Decoding Depression through EEG: Patterns, Pathways, and Solutions

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Abstract: ***Millions of people worldwide suffer from depression, a very common mental health illness with complicated and poorly understood underlying neurophysiological causes. An invaluable tool for researching the neurological underpinnings of depression is the non- invasive method of electroencephalography (EEG) to monitor brain activity. This paper explores the relationship between EEG patterns and depressive disorders, focusing on altered alpha, beta, and theta wave activities, abnormal asymmetry in frontal brain regions, event related potential power spectral density, coherence and disruptions in connectivity between the networks of brain. The main goal of the research is to find reliable neurophysiological markers that can help with depression diagnosis and treatment outcome monitoring by studying EEG data. This paper also explores Machine learning based solution for detection of depression from EEG. According to the research, certain EEG characteristics may be useful as biomarkers for depression early identification and personalized intervention. To improve mental health treatment, more research is required to improve these markers and incorporate EEG into clinical settings***
Keywords: Brainwave patterns, Frontal asymmetry, Event related potential, Power spectral density, Coherence.

I. INTRODUCTION

Depression is the most severe neurological disorder, which was characterized by prolonged period of depression, lack of enjoyment, absence of enthusiasm for activities, and a subsequent decline in quality of life. Depression can strike anyone at any time. Individuals with severe losses, abuse or other trauma are more likely to develop Major Depressive Disorder (MDD)[1].Over 280 million people worldwide suffer from depression. Women are over 50% more likely than men to suffer from depression. Every year suicide takes the lives of about 7,00,000 people. The fourth most frequent cause of mortality for people aged 15 to 29 is suicide. Suicidal thoughts have been linked mostly to mental health conditions, specifically sadness and anxiety. The rate of suicide has been rising worldwide, with 39% of adolescents experiencing the highest rates of mental illness [2,3]. Depression can manifest in numerous ways, including difficulty in concentration, thought of overwhelming regret, poor self-worth, hopelessness towards prospects, thought of suicide, disturbed sleep, variation in diet or weight and extreme exhaustion. Based on frequency and intensity, depression can be classified into mild, moderate and severe[4].Physical health has a strong influence on depression. Numerous factors that affect depression, such as lack of physical activity or excessive alcohol use, are also known risk factors for conditions like diabetes, cancer, heart disease and respiratory disorders. The difficulties associated with managing a variety of disease might also lead to depression. Early detection of depression reduces the intensity of the inherent manifestation. An early and precise assessment is crucial to the course of therapy that could enhance an individual's mental well-being. Since there is currently no commonly used laboratory test to assess depression, psychiatric patients and their healthcare providers need improved ways for diagnosing depression [5]. Semi-structured interviews between patients and healthcare professionals are a common component of conventional approaches for diagnosing and tracking depression. Following the guidelines outlined in the Diagnostic Statistical Manual for Mental Disorder-V (DSM-V) and the Beck Depression Inventory (BDI), the questionnaire sessions are completed. However, these interviews can be subjective, influenced by social stigma, cognitive impairments (i.e., memory errors), and bias (i.e., deemphasized or exaggerated symptoms). However, due to financial and geographic constraints, many individuals with depression find it difficult to get psychological healthcare services. The World Health Organisation (WHO) reports that over 75% of depressed individuals in countries do not seek professional psychotherapy. Two of the biggest obstacles that patients experience while seeking treatment are the lack of qualified medical practitioners and the stigma associated with depression in society [6].

Clinical bias and subjective self-evaluation had no effect on objective neuroimaging biomarkers, often known as "neuromarkers." In contrast to psychiatry, biomarkers—also known as physiologically based models—have been extensively employed in other medical specialties for the diagnoses, monitoring, therapy, and screening of the condition.

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These offer unbiased approximations that aid in mitigating prejudice in medical judgment. In the field of psychiatry, applying the idea of objective biomarkers could enhance diagnosis, prognosis, and the provision of efficient treatment programs. The diagnosis of anxiety and depression as mental health illnesses is the main topic of this review article, which also discusses screening for suicidal thoughts and behaviours. The incorporation of neuroimaging biomarkers into psychiatry has been the focus of recent research projects. A lot of sectors, including medical diagnosis, are seeing the emergence of artificial intelligence (AI)[7].

In order to effectively manage depression, an EEG should be regarded as a crucial tool. It can help uncover underlying and concurrent conditions as well as assist in designing a more efficient course of treatment. Since EEG can be used to diagnose conditions and direct treatment, its significance in psychiatric disorders is becoming more widely acknowledged. The goal of this study is to gather and assess data in order to enhance diagnosis and therapy in neurology and psychiatry, as well as to comprehend the connection between EEG and depression. An EEG can be used to find brain patterns or biomarkers linked to depression.

II. EEG

An EEG is a comprehensive diagnostic tool for reflecting the electrical neural activity of the brain (i.e., brain imaging tasks), due to its non-invasive strong functional neuroimaging features, which include its portability, high temporal resolution, affordability, accessibility and security [8]. It is anticipated that changes in brain bioelectrical activity will correspond with any declines in brain functionality. Therefore, several researchers have begun analysing EEG-based biomarkers that aid in extracting objective information about differences in the physiology of the brain in order to address the numerous challenges associated with accurately diagnosing several mental disorders [9].

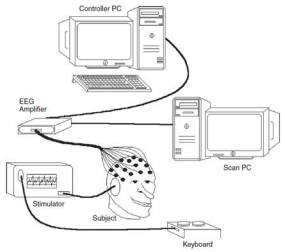

Fig. 1. Typical Setup for Brain Computer Interface (BCI)

The field of brain-computer interfaces, or BCI, has attracted a lot of attention nowadays (Fig.1). We can learn more about the mechanisms behind brain activity, cognitive functions, and the diagnosis of brain diseases by combining EEG and BCI studies [10]. Higher time resolution, less maintenance costs, and an easier to use operating system characterize EEG. Additionally, it has been utilized in the mental illness diagnosis such sadness, psychosis, and anxiety. Aberrant brain activity and clear emotional oscillation are always present in cases of depression, a mental illness with clinical symptoms including profound sadness and sluggish thinking. Thus, EEG, a technique for monitoring brain activity, can identify these aberrant events [11].

The EEG signal's frequency can be divided into 5 distinct wave bands: gamma waves (30-50 Hz), beta waves (14 -30 Hz), alpha waves (8 -14 Hz), theta waves (4-8 Hz) and delta waves (<4Hz). As various mental tasks are carried out, the EEG signals experience fluctuation in both frequency and amplitude. Fig.2 [12].

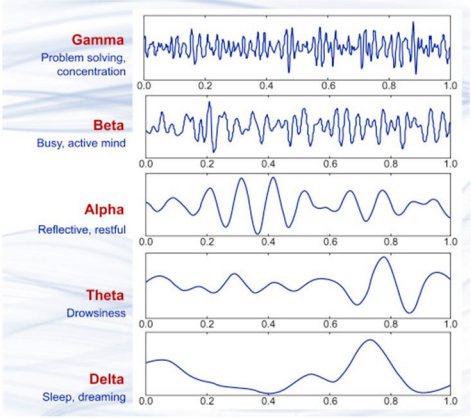

Fig 2. Different Types of Brain Waves.

The EEG responds to the biological activity of the brain's tissue, providing information on the functional state of brain. Numerous pieces of information are reflected in the EEG signal that is obtained from the various scalp regions. Somatic reactions are associated with the parietal lobe while visual reactions and auditory reactions are associated with the occipital lobe and temporal lobe respectively. Human memory, cognitive capacity, attention, responsiveness are reflected in the frontal lobe. Since the prefrontal cortex is the hub of consciousness, greater control over the forehead cortex translates into greater emotional regulation. Therefore, choosing the right location for EEG collecting is crucial for various research directions and purposes [13].

III. EEG IN RELATION WITH DEPRESSION

Currently, depression is mostly diagnosed in clinical settings using clinical manifestations and depression scales, both of which are quite subjective and prone to errors including misinterpretation and missing diagnosis. EEG signal is recorded from the surface of scalp with the help of electrodes. Studies interpreting the relationship between the brain function, mental disorder and EEG have been carried out for more than a century. The German psychiatrist, Hans Berger began studying the EEG signal in rabbits, monkeys, and later the human brain in 1926 [14]. Numerous psychological, cognitive, and neuroscientific research have demonstrated that the psychological as well as cognitive behaviour may be detected using EEG. Since the EEG signal and emotional states are closely associated, it may be able to detect changes in emotional states in real time [15].

Cole and Ray discovered a correlation between different emotional states and cognitive tasks with the EEG signal obtained from the brain's parietal lobe [16]. Low-frequency alpha waves have been shown by Klimesch et al. to represent attentional characteristics including expectancies and vigilance [17]. According to Srinivasan et al., attention level might be predicted using the frequency domain properties of EEG [18]. As a result, comprehension of how the human brain processes information and modifies emotional states depends on the EEG signal. Numerous additional researchers have emphasised the usefulness of an EEG in the categorization and selection of treatments for mood disorders [19,20].

EEG signals and depression have a multifaceted relationship which involves several key aspects of brain function and activity. According to one study, EEG can help distinguish depressed patients from those with other clinical conditions and from healthy people [21]. The activity of human brain networks may be accurately reflected by resting -state EEG (rsEEG). Numerous studies have demonstrated the significance of the rsEEG's functional connectivity and frequency domain properties in the detection of depression [22]. Investigation related to the shock components of resting state EEG signal in both normal individuals and depressed patients is examined and discovered that depression had an impact on brain activations across the cerebral cortex [23]. Quantitative EEG (QEEG) is becoming more and more important, and it's anticipated that it will be utilised to diagnose and treat mental diseases like schizophrenia and depression. Several consistent anomalies have been found in patients with depression using QEEG research [24]. Patients with depression have been observed to have reduced delta power and diminished interhemispheric coherence along with enhanced high frequency power and altered alpha asymmetry scores of frontal EEG. [25,26]

Jasper examined depression with the resting state EEG of individuals and found that there were changes in the cerebral cortex's activity when the patient experienced severe depression [27]. Nauta underlined that several facts of emotional processes were significantly influenced by the prefrontal cortex [28]. Rolls argued that emotional and motivational processes depend on the prefrontal cortex [29]. According to Harmon-Jones, left-sided prefrontal activity is linked to certain types of rage or anger that is evoked in certain situations. [30]. The EEG provides a wealth of data regarding neural electrical activity. In addition to the properties of each channel, the correlation of brain areas is important in the detection of depression. With an accuracy rate of 87.4% for MDD detection, the temporal area of the brain is the most effective. Studies confirmed that EEG signals from multi-brain regions constituting frontal, temporal and central brain area are proved to be effective in depression detection with 92.4 % accuracy. Therefore, brain region related features in EEG data are crucial for improving the accuracy of depression detection and for gaining a deeper understanding of the pathology of depression [31].

IV. BRAINWAVE FREQUENCY BANDS AND DEPRESSION

EEG measures electrical activity in the brain through different frequency bands, each associated with various cognitive and emotional states. A large section of research on EEG emphasizes on variation in specific power spectrum waves of different frequency (alpha, beta, gamma, delta and theta). To determine patterns across disorders, researcher examine several EEG investigations that report variations in bands of frequency in the resting state scenario across a variety of psychological illness, which includes depression, attention deficit with hyperactivity (ADHD), autism, anxiety, panic disorders, trauma-related stress disorder (PTSD), bipolar disorder, addiction, obsessive-compulsive disease (OCD), and schizophrenia [32].

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Majority of studies that use EEG, have postulated that individuals with MDD have some laterization in the activity of brain with anomalies in the rhythms of waves (such as alpha and theta). This would be linked to the dysfunctions in emotional capability whose alteration help in the identification of patients more prone to depression [33]. Previous research demonstrated significant changes or alteration in brainwave pattern i.e., EEG power spectrum of patients with depression in comparison to a healthy control group [34 35]

1) Delta Waves (0.5-4 Hz): These are often observed during profound sleep. Sleep disruption is strongly associated with serious depression. According to studies, people who are depressed frequently have more delta wave activity when they are awake, especially in the frontal lobes of the brain. The frequent symptoms of depressive illnesses, including as cognitive slowness, weariness, and decreased attentiveness, may be linked to this elevated delta activity [36]. During sleep patient with depression was observed to have reduced delta power as compared to healthy individuals[37]. Sleep architecture abnormalities, particularly in slow-wave sleep (SWS), which is distinguished by the presence of delta waves, are frequently linked to depression. Studies reveal that those with depression might have lower SWS, which is important for restorative sleep. Depressive symptoms may worsen as a result of non-restorative sleep caused by this decrease in SWS and delta wave activity [38]. In addition to being present during sleep, delta power is also present throughout rest and wakefulness [39]. and may play a role in autonomic system synchronization and the recognition of stimuli that are salient for motivation [40,41]. Research demonstrates that a drop in delta power is linked with the reduced negative affect in persons with severe depressive illness, indicating that delta activity may play a function in emotional regulation [42].

2) Theta Waves (4-8 Hz): Although these waves are frequently connected to light sleep and drowsiness. Majority of studies have demonstrated that theta wave activity is frequently elevated in depressed individuals, especially in the subgenual anterior cingulate cortex which is located in the frontal lobe of the brain. The symptoms of depressive illnesses, including rumination, emotional dysregulation, and cognitive deficits, may be associated with this elevated activity [43]. However, some research has also shown that depression appears to be more closely linked to a decline in theta activity, indicating that this change might be indicative of a functional disconnection in these networks that would affect the ability to process emotions [44,45]. Depression is also associated with theta imbalance between frontal and central areas which indicates the severity of the illness [46]. The non-restorative sleep that depression sufferers frequently experience may be caused by abnormalities in theta activity at the beginning of the sleep cycle or during it. Depression symptoms may worsen as a result of this disturbance in sleep quality [47]. Theta has been mentioned in a few studies as a possible biomarker of depression [48,49].

3) Alpha Waves (8-12 Hz): These waves are frequently connected with the sensations related to calmness and relaxation. Alpha activity can fluctuate in depression, such as increased power in specific brain regions, indicating a state of lower attention or disengagement. In particular, depressed group showed decreased low alpha power and increased high alpha power compared to the healthy group [50]. Alpha waves are seen to decrease in depressed patients [51]. To distinguish between the alpha wave patterns in both the groups, a 32-channel EEG was employed. In both the closed eye and the open eye circumstances, depressed group exhibited lower alpha power than that of normal group. Additionally, it was discovered that the alpha waves in frontal, parietal, occipital and temporal lobes of depression group were noticeably lower than those in the normal group. Thus, in electroencephalogram (EEG) measurements of an individual's alpha waves may serve as a biomarker for future diagnosis of depression or health issues [52].

4) Beta Waves (13-30 Hz): Active thinking, problem solving and mental activity is associated with these beta waves. Depression is sometimes associated with reduced beta activity, which may correlate with cognitive slowing, decreased concentration, and overall mental fatigue[53]. Depression may exhibit reduced beta activity in the parietal–occipital area. This area is responsible for making judgement using sensory information and may validate the negative emotional reaction to other people's assessments of oneself [54]. Depression patients maintain normal cognitive performance by strengthening their functional connectivity in high frequency bands [55]. Additionally, beta activity has been shown in clinical settings to positively correlate with the quantity of depressive episodes and can be utilized to differentiate between healthy controls and depressed patients [56].

5) Gamma Waves (30-100 Hz): High level cognitive processes like perception and consciousness are linked to gamma waves. Some studies suggest alterations in gamma activity in depression, though findings are less consistent and require further investigation [57]. The frontal and temporal regions of depressed patients exhibits a considerably higher rhythm of gamma power than those of healthy ones . While there was an increase in gamma rhythm synchronization during stress and in individuals with depression [58]. In an EEG study, individuals with high depression scores showed lower resting gamma in the anterior cingulate cortex, but in a study where participants with depression completed spatial and arithmetic tasks, gamma rose

in frontal and temporal regions. Moreover, there may be a drop in frontal cortical gamma in individuals with significant depression who are completing emotion-related tasks. In individuals with significant depression, there is an increase in the resting complexity of gamma signalling in the frontal and parietal brain [59].

V. FRONTAL ALPHA ASYMMETRY (FAA) AND DEPRESSION

One noteworthy discovery in depression research is the asymmetry in the activity of frontal alpha wave which is frequently measured by EEG as frontal alpha asymmetry (8–13 Hz). It is a means of assessing prefrontal brain activity in depression [60]. FAA is a measure of the difference in alpha power of left and right frontal regions of brain. According to a meta-analysis on resting state FAA in individuals, depression is generally linked to reduced alpha activity in the left frontal hemisphere and increased alpha activity in right frontal hemisphere are typically associated with depression [61-63].

This asymmetry has been connected to lower levels of good affect and negative emotional states. Positive emotions and approach relate to left while withdrawal and negative emotions are generally connected with right frontal activity [64-65]. Although negative findings [66] and conflicting results [67] were occasionally reported, recent investigations involving individuals with MDD were in consistent with relative right activity [68].

Furthermore, it was discovered that frontal alpha activity was specifically linked to depressive symptoms such as self-reported self-esteem and rumination [69]. In depression, alpha asymmetry of frontal lobe was considerably lower than that of parietal lobe under both open and closed eyes situations [70]. Frontal asymmetry has several theoretical and practical consequences, including the ability to predict the onset of depression. Further studies in this field can help direct the creation of neurally-informed therapies that can be useful to assess or evaluate different brain activity for better treatment. This is due to the possibility that frontal asymmetry is a neuronal system activity index in which reduction in left frontal alpha activity has been associated with a greater vulnerability to depression [71].

VI. EVENT-RELATED POTENTIALS (ERPS) AND DEPRESSION

The neural activity of brain is measured using event-related potentials (ERPs), which have good temporal resolution and may be used to look for anomalies linked to MDD. Insights into cognitive processes can be gained from ERPs, which are particular brain reactions to external stimuli [72-73]. Reduced ERP response to affective stimuli is linked to depression and depression risk. Reduced brain reactivity to monetary gain compared to loss is linked to sadness and depression risk. According to ERP research, motivational disengagement and emotional disengagement are key components of depression and risk [74-75].

1) P300 Component: An occasional, task-relevant stimulus causes a positive deflection in the human EEG known as the P300 component. Its amplitude and latency define it as a constituent of the event-related potential (ERP)[76-77]. Depression patients may have reduced P300 wave activity, which is linked to attention and cognitive processing. Diminished amplitude of the P300 component may indicate problems with emotional or sensory processing [78-79]. In individuals with depressive disorders, the delta band showed the greatest decrease in P300 at parietal locations in the ERP wave, whereas the other three frequency bands showed the greatest increase in P300 at frontal sites.[80] Reduced late positive potentials (LPPs) in response to both positive and negative stimuli are also linked to MDD [81].

2) Error-Related Negativity (ERN): A negative EEG deflection that follows an error is known as error-related negativity, or ERN. It is a part of the brain's electrical activity measured by an event-related potential (ERP)[82]. Researchers have shown that individuals who have episodic or chronic stress may have a blunted ERN and more depressed symptoms[83]. The ERN, a response to errors in cognitive tasks, can be altered in depression. Changes in the ERN may indicate difficulties in error monitoring and self-regulation. Research has also shown that when depressed individuals execute tasks involving neutral or punishing situations, their ERN amplitude may be bigger. This implies that depressed individuals might be more susceptible to punishment[84]. In comparison to the control group, MDD displayed decreased ERN amplitude and error-related theta power as well as higher error-related beta power. Reduced error monitoring and post-error inhibition are traits of MDD [85]. A negative cognitive bias, increased sensitivity to aversive experiences, decreased suppression of negative information, and hypersensitivity to negative environmental signals are some of the key characteristics of depression that may be reflected in altered ERN [86]. An additional study discovered that at high levels of intolerance for uncertainty, the relationship between depression and ERN is weaker [87].

VII. POWER SPECTRAL DENSITY AND COHERENCE IN RELATION WITH DEPRESSION

1) Power Spectral Density: Electroencephalogram (EEG) data can have their frequency content analyzed using a technique called power spectral density (PSD). It is a reliable method to classify psychiatric diseases using EEG, including depression [88]. Differences in depression can be seen in the power of several EEG frequency bands. There have been reports of decreased alpha power and increased theta power in particular brain regions, like the frontal cortex.[89]. Research has indicated that in comparison to healthy controls, depressive patients exhibit higher PSD in the beta, alpha, and theta frequency bands. These increases can be seen with or without the eyes closed, and they are most prominent in the parietal and occipital regions of the brain [90]. Depression patients and healthy controls can be distinguished from one another using quantitative EEG absolute power spectra [91].
2) Coherence: Coherence is a metric used in electroencephalogram (EEG) analysis that quantifies the degree of neural network connectivity and synchronization between two brain regions [92]. EEG investigations have revealed that the brain coherence patterns of individuals with depression differ from those of healthy individuals[93]. The connections between the frontopolar and temporal or parieto-occipital areas show increased theta and alpha coherence in individuals with depression. Additionally, the connections within and between electrodes over the dorsolateral prefrontal cortex or temporal areas exhibit stronger beta coherence [94-95]. In other research, the temporal-parietal and parietal-occipital areas of the brain show reduced alpha rhythm coherence in individuals with depression. Moreover, they exhibit reduced coherence in the frontal-temporal brain region's theta rhythm and the temporal-parietal brain region's beta2 rhythm [96]. Internalizing disorders like anxiety and depression are particularly strongly correlated with a poor sense of coherence. The altered coherence patterns observed in depression may indicate an impairment in the connectivity between the brain regions responsible for processing emotions and thought. Depression has been linked to long-term brain alterations [97].

VIII. CONCLUSION

Electroencephalography, or EEG, is a non-invasive neuroimaging method that assesses brain electrical activity. This study emphasizes the value of EEG as a tool for studying the neurophysiological basis of depression, a prevalent mental health condition. According to research, EEG signals can record distinctive brain wave patterns that may be indicative of depression, such as altered brain wave frequencies (delta, alpha, beta, theta and gamma wave activity) and amplitudes. Through the examination of EEG patterns, (such as frontal asymmetry, abnormalities in the activity of alpha, beta, and theta waves, and changes in brain connections), we have discovered promising biomarkers that could aid in the timely diagnosis and management of depression. In conclusion, considerable changes in brainwave patterns and activity are revealed by EEG studies of depression, which reflects the disorder's influence on emotional and cognitive functions.

Although electroencephalography (EEG) provides valuable insights into brain activity, it is not a diagnostic tool designed specifically for depression. It is one technique among many used to comprehend the disorder's neural foundations. Based on the findings, EEG may play a significant role in objective, non-invasive examinations of depression disorders, which could aid in more individualized and focused therapies. Personalized therapy, treatment monitoring, and early diagnosis are examples of potential applications. Promising findings from studies have included increased patient outcomes and high accuracy rates. Although these discoveries deepen our knowledge of depression, they must be combined with other diagnostic and treatment modalities since they represent only a portion of a larger clinical picture. To properly elucidate the intricate connection between EEG and depression, more investigation is required.

However, to validate these indicators across a range of populations and therapeutic contexts, more investigation is needed. It might be more useful to standardize EEG measures and investigate how these patterns alter in response to therapy to track treatment results. In the long run, the incorporation of EEG into standard clinical practice could enhance the accuracy of mental health services by offering a more sophisticated method of treating depression.

Machine learning techniques can classify healthy control and depressed patient easily when EEG features are provided. While Deep learning techniques has potential to extract features from EEG signals automatically and can more confidently classify a depressed patient from healthy control. In a country where medical facility is not available uniformly due to unbalanced ratio of doctors to patient, Using machine learning and deep learning based expert system in detection of depression from EEG signals will act as primary assistance to doctors. This expert system can act as primary assistance in detection of depression.

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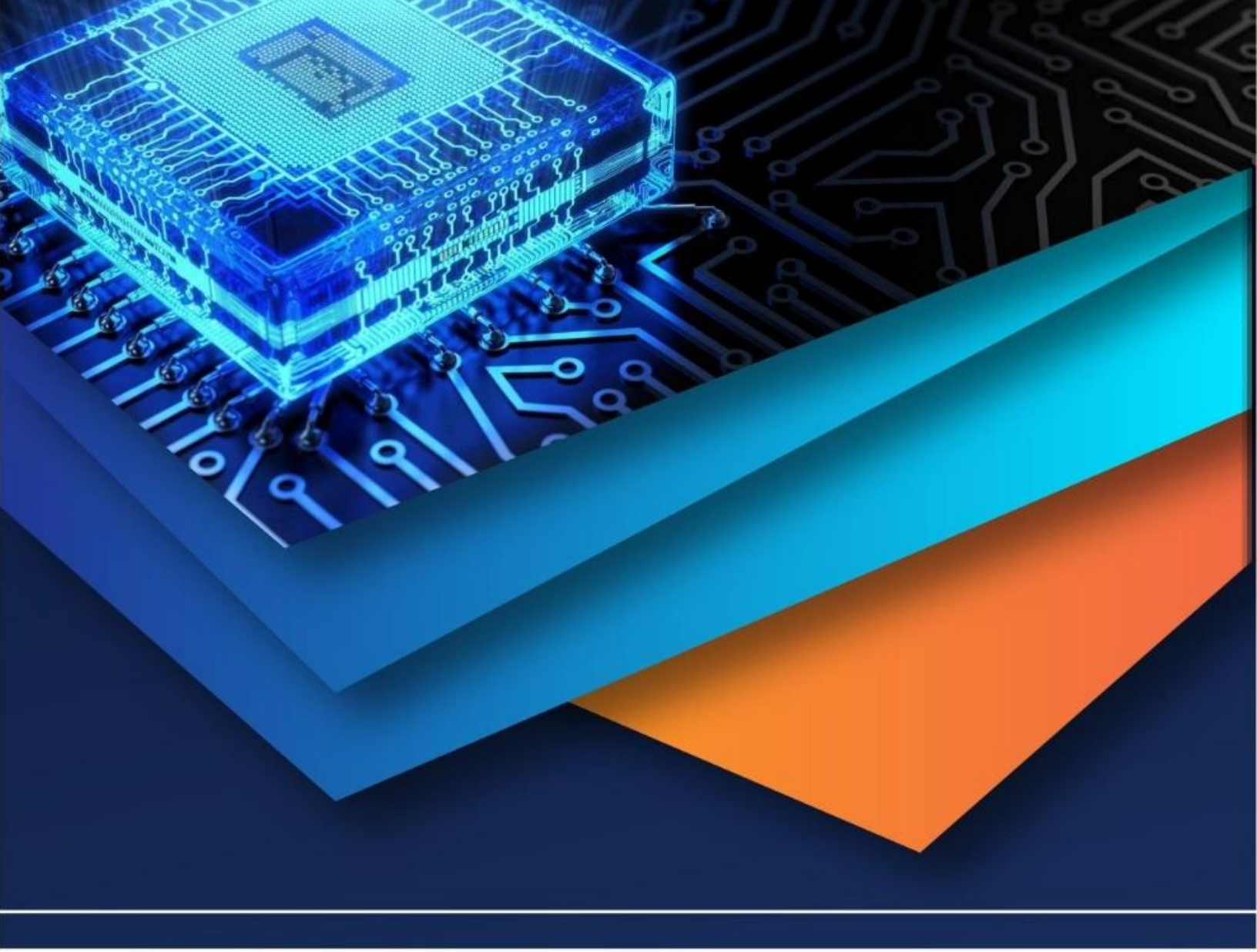

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