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Optimizing Brain-Computer Interfaces for Methampetamine Use Disorder through Quantitative Electroencephalography (QEEG) and Transcranial Doppler Analysis: Article Review

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ABSTRACT

A Brain-Computer Interface (BCI) is a system that allows a person to control external devices using only their brain activity. It works by translating brain signals into commands that can be understood by a computer. Several lines of evidence demonstrated the deleterious effect of methamphetamine (MA) on neurological and psychological functions. The use of amphetamines, such as MA, is associated with cerebrovascular complications such as cerebrovascular accidents (CVA) ,hemorrhage, hypoxic damage and vasculitis. Interestingly, while changes to cerebral blood flow (CBF) in response to acute amphetamine exposure have been reported. Transcranial Color Doppler (TCCD) is a non-invasive medical imaging technique that uses ultrasound waves to measure blood flow velocity in the major arteries of the brain, specifically within the circle of Willis. The research paper you referenced explores the use of TCCD as a potential measurement modality for BCIs. Quantitative electroencephalogram (qEEG) is a powerful tool for understanding brain function qEEG can reveal specific brain wave patterns associated with drug addiction, potentially providing insights into the neurobiological mechanisms underlying cravings, withdrawal symptoms, and relapse risk in Methamphetamine User Disorder (MUD). There is growing research interest in using Transcranial dopller as a measurement modality for BCIs.Here are some of the key considerations for using Transcranial doppler in BCIs: Mental Tasks, signal processing and classification, accuracy and reliability. Transcranial doppler provides information about blood flow in specific arteries but lacks detailed spatial information about brain activity. These patterns could vary depending on the type of drug, the severity of addiction, and individual differences. Transcranial doppler in measuring middle cerebral artery (MCA) blood flow velocity parameters (peak systolic velocity (PSV) and mean flow velocity (MFV)). qEEG can help researchers investigate the complex interplay between addiction and other brain disorders, like depression or anxiety. Characteristic qEEG in drugs addiction Increased Theta (4-8 Hz) and delta (1-4 Hz) brain waves are often associated with sleep and relaxation. However, research has shown that individuals with drug addiction may have increased theta and delta activity, particularly in the frontal and temporal regions of the brain. Altered Beta (13-30 Hz) brain waves are generally associated with wakefulness, alertness, and cognitive processing. Studies have observed both increases and

decreases in beta activity in individuals with drug addiction, depending on the type of drug, the stage of addiction, and the specific brain regions being examined. The results of this research have important practical implications for building an diagnostic and functional assement with a better understanding of an using technology.

Keywords: *BCI, QEEG, Transcranial doppler, MUD*

Pendahuluan

Methamphetamine (MA) is an extremely psychological stimulant and addictive enhancement. The increasing amount or frequency of drug use brings many negative consequences to abusers, such as dementia and psychosis disorder (Sommers et al., 2006). MA can induce neurological function and addiction because it can cross the blood-brain barrier and affect neurons such as the dopaminergic neuron, serotonergic neuron, GABAergic neuron, and glutamatergic neuron (Nash & Yamamoto, 1992). Taken together, recent evidence in vitro and in vivo studies clearly showed that MA induces neurotoxicity via induction in neurodegeneration (Cadet & Krasnova, 2009) and neuroinflammation (Gonçalves et al., 2010). In addition, several lines of evidence demonstrated the correlation between brain activity and behavior, for example, the high frequency of alpha wave during the closing of the eyes, decreased sensory input, and the inhibitory function or sensory suppression of cognitive processes such as perception, attention, working memory, and long-term memory (Klimesch, 2012). A quantitative electroencephalogram (qEEG) is a diagnostic tool that measures electrical activity in the form of brain wave patterns. Brain waves are the rhythmic electrical impulses generated when the neurons communicate with each other. Brain waves can monitor changes in brain activity as a response to the administration of drug effect to 4 brain function. A qEEG can reveal brain wave patterns that are associated with neurological symptoms such as impulsivity, cognitive inflexibility and anxiety (Newton et al., 2003).

The use of amphetamines, such as MA, is associated with cerebrovascular complications such as cerebrovascular accidents (CVA), hemorrhage, hypoxic damage and vasculitis. Interestingly, while changes to cerebral blood flow (CBF) in response to acute amphetamine exposure have been reported, there is evidence of long-term effects on CBF from MA use even in abstinent users, suggesting that the effect of MAon CBFis at least partially irreversible. Reports on the effect of MA on global or focal CBF are controversial and incomplete as seen by the variation in published data. While some researchers have reported increases in CBF after amphetamine exposure, others have shown that CBF remains unchanged (Polesskaya et al., 2011).

Transcranial Color Doppler (TCCD) is a non-invasive medical imaging technique that uses ultrasound waves to measure blood flow velocity in the major arteries of the brain, specifically within the circle of Willis (Purkayastha & Sorond, 2012). The research paper you referenced explores the use of TCCD as a potential measurement modality for BCIs. Therefore, the present study aimed to determine neurological function in the brain using qEEG brain wave measurement during cognitive assessment in MA abusers correlated transcranial color doppler (TCCD).

Metode Penelitian

Those author had Inclusion criteria included those whose main diagnosis was MUD. The subjects had only methamphetamine use for one year disorder as their primary addiction diagnosis. Exclusion criteria were current or a history of psychiatric and medical disorder, use of any medication.

Quantitative Electroencephalogram

a. EEG Acquisition

The electrodes were attached to the Electro-elastic cap according to the international 10-20 system, and 4 additional electrode placement for the electrooculography (EOG) recording were important to detect eye movement (Jasper, 1958). Both mastoid regions were used as reference sites (A1, A2). The EEG gel, QuikCell, a cellulose-based transmission, was inserted into all 37 channels attached to the Electro-elastic cap. The electrical impedance was kept below 10kΩ. This experiment arranged an EEG setting as 0.1-60 Hz for online bandpass filler and 50 Hz for notch filter. The absolute power spectrum was converted by Fast Fourier Transform (FFT) for analysis in four main frequency bands including delta wave (0.50-4.00 Hz), theta wave (4.50-8.00 Hz), alpha wave (8.50-13.00 Hz), and beta wave (13.50-30.00 Hz). Finally, the EEG data recording was interpreted in the form of a qEEG (Kropotov, 2010).

b. Quantitative EEG (QEEG) analysis

The EEG data during baseline were read and removed all artifacts manually. Artifact rejection was set at -80 to 80 μV to reject the epoch. After that baseline collection, a bandpass filter between 0.3 and 30 Hz, and spline fit were processed according to the EEG analysis protocol of the Brain Electrophysiology Laboratory & Cognitive Research Unit. The qEEG was analyzed into the power spectrum of four main frequency bands (delta, theta, alpha, and beta waves) and electrode grouping method similar 9 to the previous studies. In addition, the EEG data was presented in topographic mapping for the spatial distribution of EEG power in each frequency band. The EEG power was analyzed over including the prefrontal cortex (FP1, FP2), Lt. frontotemporal (F7, T3), frontal lobe (F3, Fz, F4), Rt. frontotemporal (F8, T4), central (C3, CZ, C4), and parietal (P3, Pz, P4) regions (Kraiwattanapirom et al., 2022).

Transcranial Doppler

The bilateral MCAs of the subjects were insonated via the trans-temporal window (TTW) at two standardised imaging depths (regions of interest, ROI): (Sommers et al., 2006) proximal MCA segment at the bifurcation, and (Liang & Rutledge, 1982) distal portion of the MCA that could be visualised on the Transcranial doppler with a detectable spectral waveform across the Transcranial doppler techniques. The ROIs were identified by first scanning using the Transcranial doppler technique at three TTW locations (anterior, middle, and posterior), with the subject lying in a supine position as described in previous studies. The Transcranial doppler protocol involved performing, firstly, an axial B-mode scan of the head, which was followed by color and spectral Doppler scans, respectively. The ultrasound machine settings for the current study involved optimising the main parameters of B-mode ultrasound, such as power output, frequency, overall gain, time gain compensation (TGC), focusing, and depth (Gunda et al., 2024).

Hasil dan Pembahasan

Quantitative Electroencephalography in Methamphethamine Use Disorder (MUD)

The qEEG recording during the resting state (eyes-closed and eyes-open) has been used for detecting the state of consciousness and cerebral function. Biomarkers of neuroimaging techniques are not only used to distinguish those suffering from drug addiction from healthy controls, but they are also widely used to evaluate the efficacy of abstinence, exercise, and medical interventions. The biomarkers of QEEG signals that have been shown to characterize the brain activity of those suffering from METH addiction are listed in Tables 1. The biomarkers were determined by comparing the recorded EEG signals from patients with a METH addiction with those of healthy controls. The brain signals were recorded when participants received various METH-related cues, after conducting cognitive tasks, or during resting states. The EEG biomarkers that can identify the patients with a METH addiction can be categorized into three types based on the analysis approaches used. First, the time-domain EEG signals can be converted to frequency-domain signals to reveal the spectral information of QEEG sub-bands (Chen et al., 2023). The sub-bands of each frequency range represent different conditions affected by METH (Table 1). The entropy of the EEG signals at a specific frequency range can be derived from the spectrum of that frequency range (Newton et al., 2003). The second type of biomarkers are based on time-domain signals. As EEG records neural activity on a millisecond timescale, the neural signals triggered by stimuli (visual, audio, etc.) show specific wave forms, namely the event related potential (ERP) (19,20).

Tabel 1. QEEG signals in frequency and time domains on patients with methamphetamine addiction.

REFERENCE	COMPARISON CONDITION	GROUP FOR COMPARISON	NUMBER OF THE ELECTRODES AND THEIR LOCATION	CHARACTERISTIC BANDS
Newton et al	Eye-closed resting state during abstinence	METH vs HC	35 electrodes distributed across the scalp	Increases: delta and theta bands across the scalp
Newton et al	Eye closed and cognitive task	METH vs HC	35 electrodes distributed across the scalp	Increases: theta band increases with the increasing of the reaction time of cognitive task
Ding et al	Drug-related and Neutral VR	METH vs HC	5channels (Fpz,AF7,AF8,TP9,TP10)	(1)Increases:beta and gamma Decrease: delta and alpha

				(2)Decrease: delta,theta,and alpha
Hwang et al	Eye closed	METH vs HC	32 channels	Absolut power: increase alpha, high beta Relative power: increase theta, alpha, beta
Kraiwattanapirom et al	Eye open 10 min, eye closed 5 min.	METH vs METHP	37 channels	Resting state: increae absolute power of an alpha wave in all brain area Eye open: increase in theta right frontal and right temporoparietal , , increses delta et regio righ frontal
Di Zhao et al	Resting state, eye closed	METH craving vs HC	128 channel	Increased beta in relative power 1-3 month

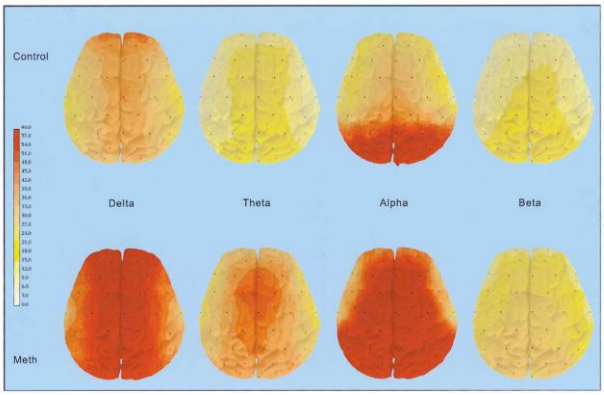
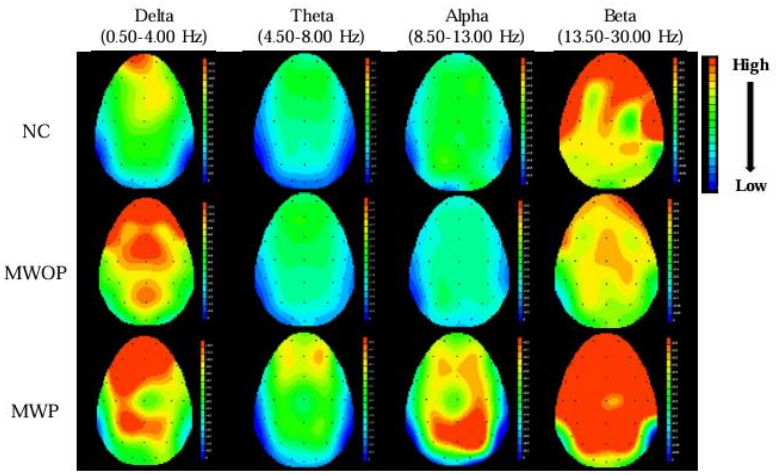


Fig 1. Topographic maps of power in the delta, theta, alpha and beta bands. QEEG absolute power is mapped across the scalp. Increasing power is indicated by increased color intensity, as indicated by the color legend. (18)

A



B

Wave	Area	Absolute power of brainwave (μV^2/Hz)		
		NC	MWOP	MWP
Delta	PFC	9.99 ± 2.93	10.56± 4.42	18.58 ± 13.05*,#
	Lt. FT	4.78 ± 1.39	7.69 ± 3.84	9.12 ± 5.68*
	Frontal	8.44 ± 1.78	9.15 ± 3.68	12.74 ± 5.91*
	Rt. FT	5.39 ± 1.86	8.13 ± 4.42**	9.43± 3.67**
	Parietal	4.90 ± 1.09	7.50 ± 3.68	8.01 ± 3.80*
Alpha	PFC	1.49 ± 0.71	1.27 ± 0.84	3.48 ± 2.50**,##
	Lt. FT	0.98 ± 0.44	0.85 ± 0.55	2.26 ± 2.17*,#
	Frontal	1.76 ± 0.85	1.38 ± 0.94	3.95 ± 3.11**,##
	Rt. FT	1.08 ± 0.57	0.94 ± 0.52	1.94± 1.49*,#
	Central	1.61 ± 0.84	1.32 ± 0.90	3.52 ± 2.88*,##
	Parietal	1.76 ± 1.27	1.34 ± 1.05	4.59 ± 4.81*,##
Beta	PFC	0.79 ± 0.42	0.47 ± 0.23	1.06 ± 0.86#
	Frontal	0.61 ± 0.29	0.44 ± 0.16	0.90 ± 0.60##
	Central	0.51 ± 0.21	0.42 ± 0.16	0.66 ± 0.32#
	Parietal	0.43 ± 0.17	0.39 ± 0.17	0.64 ± 0.42#

Fig.2 **A.** The topographic distribution of absolute power of 4 frequency bands of brainwave during eyes-open in normal control (NC), methamphetamine without psychosis (MWOP), and methamphetamine with psychosis (MWP) subjects, respectively. The red areas indicate a significant increase in power (A). The data of significant increase in absolute power (mV2/Hz) during eyes-open were shown as mean ± SD. **B** *p < 0.05, **p < 0.01 compared with the control group and #p < 0.05, ##p < 0.01 compared with the MWOP (Kraiwattanapirom et al., 2022).

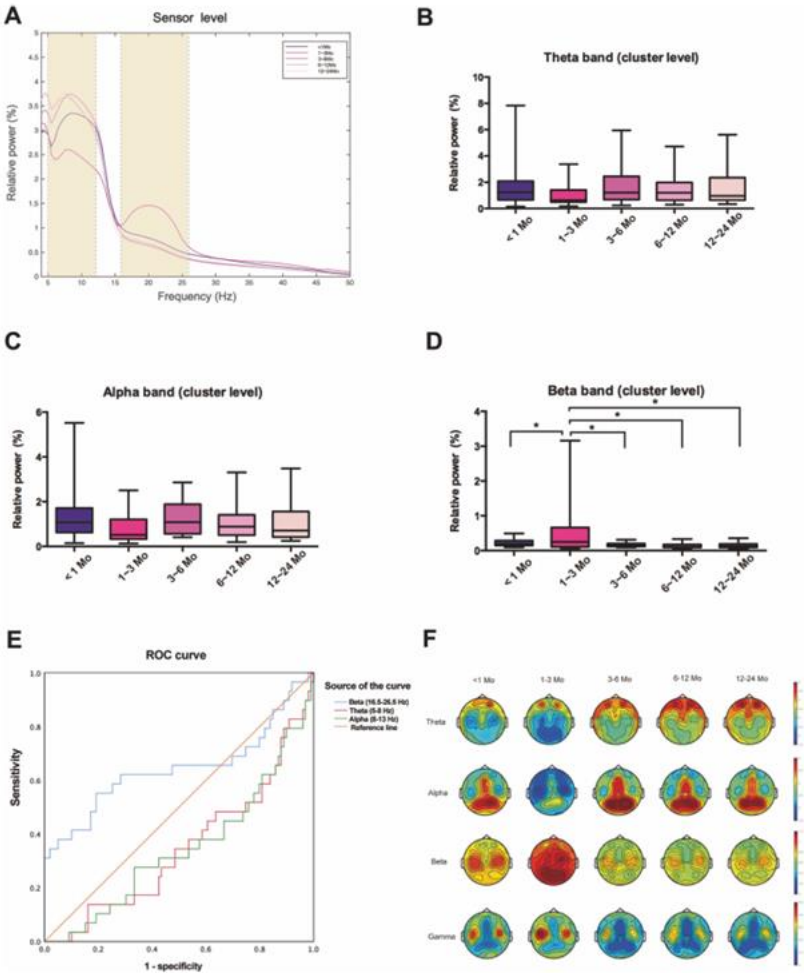


Figure 3. Analyses on sensor level. A Spectral profiles of participants with MUD. The yellow shadow indicates the frequencies at which the power of 1–3 Mo group was significantly different from other four methamphetamine abstinence groups at p<0.0025. Patients from Grou2 demonstrated reduced relative power in theta and alpha and increased relative power in the beta band. B The relative power , theta of the largest cluster band. C The relative power alpha of the largest cluster. D The relative power beta band. E Receiver operating characterictic curves (ROCs) of ossilation for the classification of incubation from other abstinence states. Beta frequency band : AUC =0.643,*p= 0.019.* F Topographical maps of relative power among fiv abstinent methamphetamine group.

In the QEEG spectrum analyses summarized in Table 1, one approach is that an individual electrode is inspected only when the numberof electrodes is small. Alternatively, the spectrum of individual electrodes is calculated, then representative channels are selected for further investigation (Shahmohammadi et al., 2016). In studies with larger numbers of electrodes, the average EEG spectrum of all electrodes is often investigated. Lu et al. and Minnerly et al. studied changes in the EEG spectrum of different brain regions. The former separated the brain into four areas, whereas the latter separated the cortices using five different approaches. A lower number of EEG channels reduces the preparation time when the region of interest is well known. However, increasing the number of electrodes allows for studying FCacross various

brain regions.

Cerebral perfusion in Methamphethamine Use Disorder (MUD)

Methamphetamine's name derives from the additional methyl group on its chemical structure, as compared to amphetamine. This added methyl group enhances lipid solubility, allowing for more rapid transit across the blood brain barrier, increased potency, and longer lasting central nervous system stimulant effects. The terminal half-life of meth is approximately 10 h with significant variability among individuals due to its hepatic metabolism via cytochrome p450 2D6 (Cruickshank & Dyer, 2009). Compared to cocaine, which has a half-life of only 0.5–1.5 h, meth has a relatively long effect (Roque Bravo et al., 2022). This model is supported by the hypertensive pattern of intracerebral hemorrhage commonly observed in patients with meth-related ICH, even among those without a history of essential hypertension. While not as common as hemorrhagic stroke, ischemic stroke has been reported as a sequela of both recent and chronic meth use in multiple case series (Ho et al., 2009). The incidence of meth-associated ischemic stroke is unknown and represents a current knowledge gap. Two population-based studies report a lack of statistical association between meth use and ischemic stroke (Westover et al., 2007). It must be noted that both studies identified their cohorts using ICD codes for hospitalized patients, which introduces bias in patient selection. Huang et al. (Huang et al., 2016), who conducted a 10-year follow up study in Taiwan with a meth cohort, posited that an even longer duration of monitoring may be needed to see the association between meth use and ischemic stroke. In terms of stroke subtypes, (Zhu et al., 2023). Compared meth and non-meth users with ischemic stroke admissions at a single center in California and found no significant difference in the percent of strokes from small vessel disease (31% vs. 28%), large vessel disease (25% vs. 24%), or cardioembolism (34% vs. 46%). They did, however, find increased burden of microvascular ischemic disease on MRI in meth users compared to a propensity matched control group (Zhu et al., 2023). Route of administration is rarely reported in the literature, so it is unclear if this has any impact on the risk of neurovascular disease. In a small case review of 17 ischemic strokes, patients with inhalational use represented 4 times the number of cases compared to oral use or injection use (Lappin et al., 2017). Further investigation is warranted as the small case numbers in these studies increase the risk of bias.

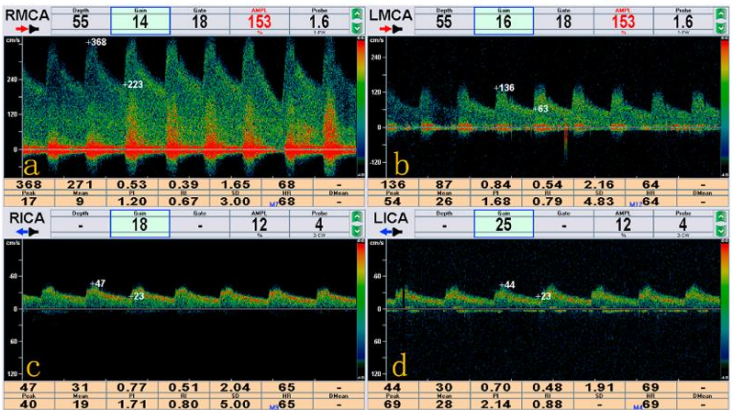


Figure 4. The mean flow velocity (MFV) of the RMCA M1 segment (2a) was 271 cm/s, and the

MFV of the RICA extracranial segment (2c) was 31 cm/ s, with a Lindegaard ratio of 8.7; The MFV of the LMCA M1 segment (2b) was 87 cm/s, and the MFV of the LICA extracranial segment (2d) was 30 cm/s, with a Lindegaard ratio of 2.9 (45).

DISCUSSION

Quantitative electroencephalograms (qEEG) have been studied for various disease groups, but it is true that research on methamphetamine is still insufficient. The slow wave in the group of methamphetamine-dependent patients increased and was associated with impaired neurocognitive functions such as low executive function test scores, and that these changes improved with biofeedback training In a study on attention deficit hyperactivity disorder, etc., it was found that the ratio between each EEG in quantitative EEG was also significant as an indicator of attention concentration. In previous studies, it has been argued that alpha activity reflects arousal, and theta and beta activity reflect task- or situation-specific activation changes due to stimulus processing. It has also been known that task-induced increases in theta output and the phase relationship between theta and gamma oscillations are important for memory processes, especially episodic long-term memory and working memory. Low levels of theta activity and high alpha activity during resting state have been shown to predict increased theta ability during task performance and improve cognitive ability. It has also been reported that alpha-theta ratio reflects cognitive decline in Parkinson's disease and dementia. These indicators are being used in biofeedback research and treatment. Previous methamphetamine studies have had the limitation of a small sample size, which is because methamphetamine dependent patients are subject to judicial processing, which limits the recruitment of research subjects, and this appears to be a limitation of related studies.

Some studies had explored QEEG biomarkers when subjects had their eyes closed but were not asleep; this is done to reduce the disturbance due to non-task related visual stimuli (Minnerly et al., 2021). Other studies report the identification of biomarkers specifically when the subjects had received cues (Ding et al., 2020). Some studies included cognitive tasks in the experiment protocols. However, most of these studies only analyzed the correlation of the level of cognitive impairment (e.g., the reaction time and the response accuracy) and the QEEG spectrum (Kalechstein et al., 2009). Few studies have monitored the variation in the EEG spectrum during cognitive tasks (Ding et al., 2020). For future applications in closed loop neuromodulation systems, the biomarkers found when the participants were simultaneously receiving cues may be more helpful than, e.g., at a resting state, as the use of cues can more accurately simulate the conditions of having a desire for a drug. In addition to the QEEG signal, FC is often studied in the resting state as well. In the task state, the connectivity needs to be analyzed in every pair of channels at every point of interest, resulting in a heavy computational load. This is because the brain is engaged in various tasks at different stages along with the task. Only the data of a selected resting time period is calculated in the resting state.

The mechanism of ischaemic stroke in methamphetamine addicts may involve cerebral vasospasm and Transcranial Doppler before treatment indicated that the RMCA blood flow rate increased significantly supports cerebral vasospasm, Transcranial doppler imaging to assess cerebral blood flow during and after each headache following methamphetamine

administration is currently lacking. Once inside the brain, meth increases release and blocks reuptake and degradation of the monoamine neurotransmitters: dopamine, serotonin, and norepinephrine. Meth induces a dose-dependent hypertensive surge, which may lead to direct damage and rupture of small penetrating arteries (Ho et al., 2009). Meth is also known to act upon aminergic receptors like trace amine-associated receptor 1 (TAAR1), which might also play a role in meth-induced cerebral vasoconstriction (Kevil et al., 2019). Despite the well described physiology of meth inducing vasoconstriction, there are few cases in the literature of hemorrhage due to meth-induced reversible cerebral vasoconstriction syndrome (RCVS), and those that are reported have occurred in the setting of other illicit substances and serotonergic drugs (548. In addition to acute hypertension and vasospasm, meth induces blood brain barrier (BBB) breakdown (Turowski & Kenny, 2015).

Meth cardiomyopathy also disrupts electrical conduction, leading to arrhythmias. QTc prolongation was the most frequent electrocardiogram abnormality at 27% in a cohort study of 158 meth users. Atrial fibrillation is a major source of cardioembolic strokes, and a 2022 database analysis of California residents showed meth users had an 86% increased risk of atrial fibrillation diagnosis, as compared to their non-user counterparts. Importantly, the cardiotoxic effects of meth have been documented with acute, chronic, and binge-pattern meth use, but the severity of use is an independent predictor of outcomes. Infective endocarditis (IE) is another possible etiology for ischemic stroke in people using intravenous meth. Reports of resultant stroke are difficult to find in the literature, but Johnstone et al. used a Canadian cohort to compare IE patterns for people who inject opioids and stimulants. They found that, while 66% of opioid users with first time IE developed a right heart infection, there was an even distribution of left and right-sided heart disease among stimulant users (75% meth but also included cocaine, buproprion, and methylphenidate), creating increased potential for embolic stroke. Chapman et al. described a young man with 6 months of sustained meth use and a resultant severe cardiomyopathy who presented with a cardioembolic right MCA occlusion. Loewenhardt et al. described a chronic meth user who presented with an MCA occlusion that was treated with balloon angioplasty without complication (Loewenhardt et al., 2013). Outside of the case presented in this paper, there is no mention of vasospasm as a complication of angiographic interventions in the literature.

Conclusion

Reseaarch on QEEG and Transcranial Doppler is still very limited, the structure of the brain greatly influences the function of brain cells. Previous studies provide an overview of brain wave function and brain perfusion in methamphetamine addiction. It is hoped that further research can collaborate QEEG and Transcranial Doppler

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