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Electrical Capacitance Volume Tomography (ECVT) for real-time brain activity monitoring: a comparative frequency analysis study

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ABSTRACT

Current brain imaging modalities such as CT scan and MRI, while providing excellent anatomical detail, have limitations in real-time functional brain activity monitoring. Electrical Capacitance Volume Tomography (ECVT) emerges as a promising non-invasive, cost-effective alternative for dynamic brain activity assessment. This study aims to evaluate the sensitivity of ECVT technology in detecting brain motor activity variations across different frequencies and determine the optimal frequency for brain wave fluctuation measurement. A 16-electrode ECVT helmet system was employed to monitor brain activity in subjects performing motor stimulation tasks including hand gripping, imagined movement, and control conditions (water and empty space). Measurements were conducted at three frequency variations: 500 kHz, 1 MHz, and 5 MHz. Data acquisition involved multiple channel combinations (C14-16, C14-15, C14-13, C14-12, C16-15, C16-9, C16-8, C16-10) with voltage peak-to-peak (Vpp) measurements recorded via oscilloscope. The 500 kHz frequency demonstrated the highest sensitivity in detecting brain activity variations. Distinct Vpp patterns were observed across different motor tasks, with imagined movement producing the highest values, indicating increased neural activity. The ECVT system successfully differentiated between active motor tasks and resting states. ECVT at 500 kHz frequency shows superior sensitivity for brain activity monitoring, offering a portable, low-cost alternative to conventional neuroimaging modalities for real-time functional brain assessment.

Keywords:
ECVT, Brain Imaging, Motor Activity, Tomography, Neuroimaging, Frequency Analysis.

Introduction

The advancement of tomographic technology began in the latter half of the 20th century, driven by increasing demands for sophisticated medical imaging methods. The development of computers in the 1940s and 1950s paved the way for innovations in imaging technology, while research in X-rays and magnetic resonance continued to evolve. These developments culminated in the 1970s with the introduction of computed tomography (CT scan), enabling detailed three-dimensional imaging of body organs, and Magnetic Resonance Imaging (MRI) technology, which utilizes magnetic fields and radio waves to produce highly detailed images of soft tissues (Hounsfield, 1973; Lauterbur, 1973).

CT scan and MRI represent two medical imaging technologies frequently employed in clinical practice for diagnosing various disease conditions. Both possess the capability to generate highly detailed and sensitive body images, significantly assisting in detecting and analyzing various health conditions (Berger et al., 2019). CT scan utilizes X-rays to create cross-sectional body images, while MRI employs magnetic fields and radio waves to generate detailed images of internal body structures. Both modalities are non-invasive, requiring no surgical intervention or insertion of instruments into the body (McCollough et al., 2015).

However, both CT scan and MRI have several limitations that must be considered. Neither can directly visualize brain activity, only anatomical brain structures. Additionally, CT scan uses potentially tissue-damaging X-rays, while MRI employs strong magnetic fields that may cause nerve stimulation and allergic reactions to contrast agents. Examination time is also a critical factor, with MRI requiring 45 minutes to 1 hour compared to CT scan's approximately 10 minutes. Cost-wise, both MRI and CT scan are expensive, with MRI generally costing more than CT scan (Parizel et al., 2015; Wardlaw et al., 2014).

PT. Ctech Lab Edwar Technology represents a leading company in developing Electrical Capacitance Volume Tomography (ECVT) and Electro-Capacitive Cancer Therapy (ECCT), as well as medical products for cancer treatment. The company plays a pivotal role in developing and manufacturing ECVT, an electronically managed transmission technology, for vehicular industries and medical applications, with particular dedication to creating innovative medical devices, especially those related to cancer treatment (Suprianto et al., 2018).

ECVT as a scanning tool operates through capacitance measurement concepts to map three-dimensional electrical property distribution, specifically relative permittivity, of a medium within an electric field. Unlike other scanning methods such as CT-Scan using X-rays, ultrasound with ultrasonic waves, and MRI utilizing magnetic field waves, ECVT relies on electric fields as the primary element in generating useful visual representations (Abdullah et al., 2017; Wang et al., 2015).

ECVT represents an innovation in scanning technology offering a unique approach utilizing electric fields. Importantly, ECVT operates with a power supply of 220 V, while the electric field intensity directed to the human body remains significantly lower than the safe limits established by global health regulations, approximately 87 V/m (ECVT) compared to the WHO safe limit of 5000 V/m (World Health Organization, 2014).

This research aims to investigate signals during motor simulation including gripping, imagined movement, and cartoon observation with frequency variations of 500 kHz, 5 MHz, and 1 MHz to determine sensitivity in measuring brain wave fluctuations. While MRI and CT Scan focus primarily on anatomical visualization, Electro-Cortical Vector Tomography (ECVT) emerges as a promising solution with its capability to capture physiological aspects of brain activity in real-time and rapidly (Rahim et al., 2020; Zhang et al., 2019).

Methods

Equipment and Materials

The following equipment and materials were utilized in this research is ECVT helmet with 16 electrodes (Figure 1), hantex signal generator, digital oscilloscope, connection cables, laptop computer for display, distilled water (control medium), and equipment stand.

Figure 1. 16-Electrode ECVT Brain Scanning System

ECVT System Configuration

The Brain ECVT (Electrical Capacitance Volume Tomography) system employed in this study represents an ECVT system designed for studying electrical activity of the human brain. ECVT is a dynamic volume imaging technique developed based on the ECT (Electrical Capacitance Tomography) system. Initially, ECVT was utilized for imaging dielectric distribution of high-contrast dielectric materials. In industrial applications, ECVT has been used for studying gas-solid fluidized bed systems and gas-solid Circulating Fluidized Bed (CFB) to obtain three-dimensional multiphase flow images (Yang et al., 2021).

The capacitance tomography sensor Brain ECVT consists of 16 electrodes designed in helmet form. These electrodes function as plates similar to capacitors, while the internal space serves as the dielectric. One electrode plate acts as the charge source while others are alternately activated as detectors to measure capacitance, thereby obtaining permittivity distribution for reconstruction into 3D images (Abdullah et al., 2018).

ECVT utilizes the properties of a soft field called the 'edge effect' of electric fields distributed in three-dimensional space. This edge effect contains valuable information that can be extracted using soft-computing algorithms for imaging purposes with low-level energy sources. The principles of Electrical Capacitance Volume Tomography consist of two steps: (1) measuring capacitance between pairs of capacitive electrodes arranged to include a 3D sensing domain, and (2) reconstructing volumetric permittivity distribution within the 3D sensing domain from measured capacitance using specific algorithms (Wang et al., 2019).

Electrode Placement and Data Acquisition

Standard placement follows recommendations by the American Electroencephalography Society. The standard numbering system places odd-numbered electrodes on the left side of the scalp and even-numbered electrodes on the right side. The 10% and 20% figures refer to distances between adjacent electrodes placed at 10% or 20% intervals on the skull. Electrode locations are determined by dividing this perimeter into 10% and 20% intervals. F represents the frontal region, C represents the central area, P is parietal, O is occipital, and T is temporal. Z refers to electrodes placed on the midline (Jasper, 1958).

Based on anatomical and physiological theory, a helmet was used for data acquisition, with transmitter and receiver channel pairs related to brain regions with the highest activity according to category. In the 16-channel ECVT helmet, channel pairs for carrier signal cables and signal cables captured by the oscilloscope included: C14-16, C14-15, C14-13, C14-12 and C16-15, C16-9, C16-8, C16-10 for motor stimulation.

Experimental Protocol

Subjects were seated in a relaxed state with the ECVT helmet positioned on their heads. Data acquisition was performed for each channel and activity with frequency variations of 500 kHz, 1 MHz, and 5 MHz. Subjects performed the following stimulations:

1. Imagined Movement: Thinking about hand movement without performing the actual movement
2. Physical Movement: Performing hand gripping movements
3. Control Conditions: Water and empty space measurements

Data were saved as ".txt" files containing voltage values recorded by the oscilloscope. Six measurement data acquisitions were performed in this research. Data processing was conducted using Google Spreadsheets, followed by data plotting to create graphs for determining the most sensitive frequency and channel.

Data Analysis

Voltage peak-to-peak (Vpp) values were recorded and analyzed for each experimental condition. The sensitivity matrix data from the 16-sensor ECVT helmet sensor were compared across different frequencies. Statistical analysis focused on identifying significant differences between experimental conditions and determining the optimal frequency for brain activity detection.

Results and Discussions

Results

Frequency Response Analysis

The experimental data obtained from measurements at three different frequencies (500 kHz, 1 MHz, and 5 MHz) demonstrated varying sensitivity levels for different motor activities. Tables 1 present the complete dataset for all experimental conditions.

- At 500 kHz frequency, significant differences were observed between experimental conditions, particularly between hand gripping, imagined movement, and control conditions (water and empty

space). The results showed distinct Vpp patterns that could reliably differentiate between active motor tasks and resting states.
- At 1 MHz frequency, moderate sensitivity was observed with some differentiation between experimental conditions. However, the signal-to-noise ratio was lower compared to the 500 kHz measurements.
- At 5 MHz frequency, minimal sensitivity was observed with no significant differences between experimental conditions and control measurements, indicating poor performance at this frequency range.

Table 1. The experimental data obtained from measurements at three different frequencies

Frequency	Channel							
	14-6	**14-12**	**14-13**	**14-15**	**16-8**	**16-9**	**16-10**	**16-15**
Hand Gripping								
500 kHz	10.03	10.04	10.03	10.02	10.03	10.03	10.03	10.02
1 MHz	9.87	9.88	9.88	9.87	9.86	9.88	9.88	9.87
5 MHz	8.47	8.50	8.47	8.54	8.48	8.54	8.52	8.51
Imagined Movement								
500 kHz	10.03	10.04	10.04	10.02	10.03	10.04	10.04	10.03
1 MHz	9.88	9.88	9.88	9.88	9.87	9.88	9.88	9.87
5 MHz	8.50	8.50	8.53	8.47	8.46	8.50	8.62	8.57
Water								
500 kHz	9.84	9.86	8.24	8.21	9.92	9.93	9.95	9.89
1 MHz	9.79	9.83	8.19	8.16	9.79	9.82	9.94	9.78
5 MHz	8.43	8.45	7.04	7.02	8.42	8.44	8.42	8.41
Empty								
500 kHz	9.95	9.96	9.96	9.97	9.95	9.96	9.96	9.94
1 MHz	9.95	9.96	9.96	9.94	9.95	9.96	9.96	9.94
5 MHz	8.52	8.50	8.55	8.48	8.46	8.55	8.50	8.46

Motor Activity Detection

The 500 kHz frequency demonstrated the highest sensitivity in detecting brain motor activity variations. Figure 2 illustrates the Vpp variations for different motor stimulation tasks at 500 kHz frequency. The graphs show distinct patterns for each experimental condition:
- Hand Gripping: Produced the lowest Vpp values, indicating reduced brain activity during physical motor execution
- Imagined Movement: Generated the highest Vpp values, suggesting increased neural activity during motor imagery
- Control Conditions: Water and empty space measurements provided baseline references

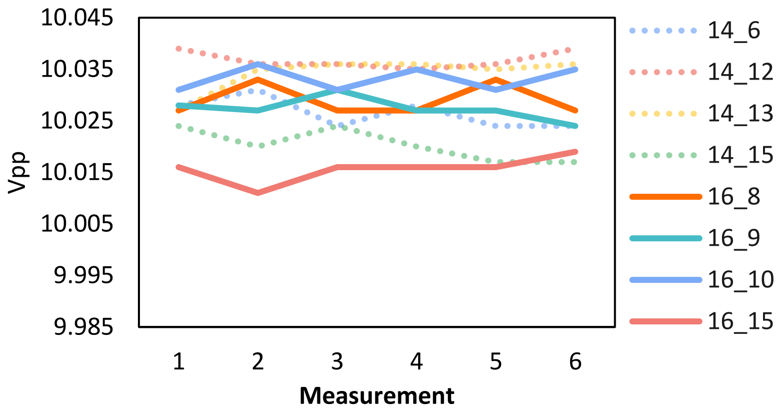
Channel Sensitivity Comparison

Among the tested channel combinations, channels C14-16, C14-15, C16-15, and C16-9 showed the highest sensitivity to motor-related brain activity changes. These channels correspond to brain regions associated with motor control and planning, consistent with neuroanatomical expectations.

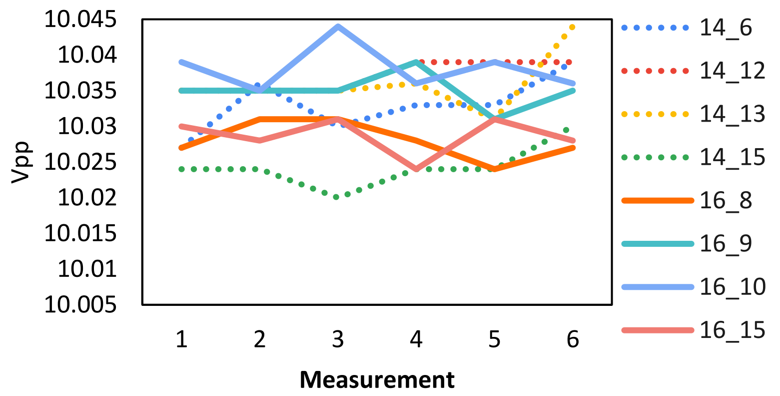
The electric field distribution for each sensor pair showed variations reflecting responsive regions to the 16x16x16 voxel measurements. The sensitivity matrices revealed that the 500 kHz frequency provided optimal signal differentiation across all tested channel combinations.

Discussion

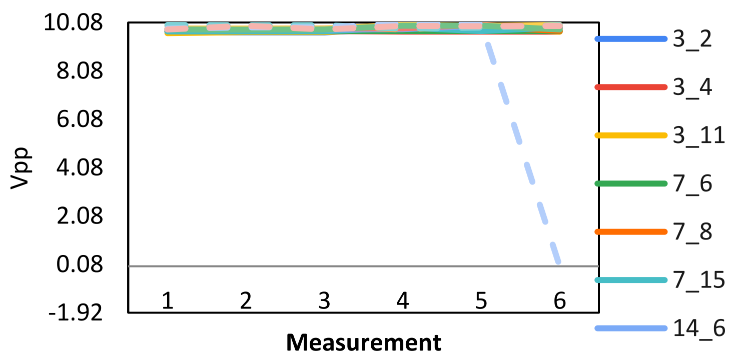
The results demonstrate that ECVT technology at 500 kHz frequency offers superior sensitivity for real-time brain activity monitoring compared to higher frequencies. This finding aligns with the electrical



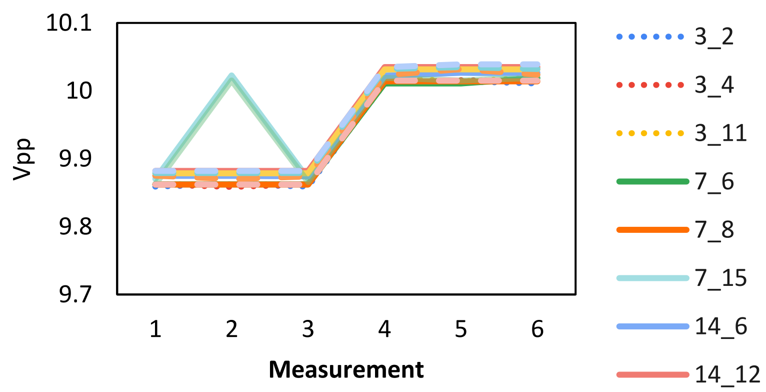
(a)



(b)



(c)



(d)

Figure 2. The Vpp variations for different motor stimulation tasks at 500 kHz frequency in (a) Hand Gripping, (b) Imagined Movement, (c) Water and (d) empty

properties of brain tissue, where lower frequencies provide better penetration and signal detection capabilities (Gabriel et al., 1996).

The observed differences in Vpp values across different motor tasks reflect the underlying neurophysiological processes. During imagined movement, increased cortical activity results in higher electrical field variations detectable by the ECVT system. This corresponds to findings in motor imagery research using traditional neuroimaging methods (Decety & Jeannerod, 1995).

The lower Vpp values during actual hand gripping, compared to imagined movement, can be attributed to the focused nature of motor execution versus the distributed cortical activation during motor planning and imagery. This phenomenon has been previously documented in EEG and fMRI studies (Pfurtscheller & Neuper, 1997).

ECVT's advantages over conventional neuroimaging modalities include:

1. Real-time capability: Instantaneous data acquisition and processing
2. Cost-effectiveness: Significantly lower operational costs compared to MRI or CT
3. Portability: Compact system suitable for various clinical settings
4. Safety: Non-ionizing radiation with minimal health risks
5. Non-invasive: No contrast agents or radiation exposure required

However, limitations include lower spatial resolution compared to MRI and the need for further validation studies to establish clinical reliability and standardized protocols.

The 500 kHz frequency's superior performance suggests optimal interaction with brain tissue electrical properties. This frequency range appears to provide the best balance between signal penetration and sensitivity to neural activity changes, making it suitable for brain-computer interface applications and neurological monitoring.

Conclusion

This study demonstrates that Electrical Capacitance Volume Tomography (ECVT) at 500 kHz frequency provides optimal sensitivity for real-time brain motor activity monitoring. The technology successfully differentiated between various motor tasks including hand gripping, imagined movement, and control conditions. Key findings include:

1. Optimal Frequency: 500 kHz demonstrated superior sensitivity compared to 1 MHz and 5 MHz frequencies
2. Motor Activity Detection: Clear differentiation between active motor tasks and resting states was achieved
3. Channel Sensitivity: Specific electrode combinations showed enhanced sensitivity to motor-related brain regions
4. Clinical Potential: ECVT offers a cost-effective, portable alternative to conventional neuroimaging for functional brain assessment

Future research should focus on expanding the subject population, investigating additional frequency ranges, and developing standardized protocols for clinical implementation. The integration of advanced signal processing algorithms and machine learning techniques could further enhance ECVT's diagnostic capabilities.

ECVT technology represents a promising advancement in holistic medical technologies, bridging the gap between sophisticated neuroimaging and practical clinical applications. Its potential for brain-computer interfaces, neurological rehabilitation, and continuous brain monitoring warrants continued investigation and development.

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Conflicts of interest

The author declares no conflicts of interest.

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