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Review

Microwave-Based Dielectric Properties as an Electrophysiological Biomarker: Future Perspectives

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Abstract: Electrophysiology is the study of the electrical properties of biological tissues, which involves the movement of ions across cell membranes. The analysis of the movement of electrical charges through the body has a wide range of biomedical applications, such as diagnosing and planning treatment in cardiovascular, nervous systems, muscular, and gastrointestinal disorders. The dielectric properties of biological tissues change according to the water content in the tissue and are measured as permittivity and conductivity relative to the frequency of the electrical field. This principle has been applied in diagnostics and therapeutics using microwave energysuch as imaging and ablation, etc. This review article summarizes the potential use of measuring dielectric properties using microwave imaging and how it can augment electrophysiological studies in medicine.

Keywords: microwaves; dielectric properties; permittivity; conductivity; microwave imaging; electrophysiology; action potential; refractory period; pacemaker; excitable cells

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1. Introduction

Electrophysiology (EP) is the study of the electrical properties of biological cells and tissues [1,2]. Understanding this area of study is vital to understand many organs, including the heart, brain, and gut, which depend on the electrical signals generated and transmitted across these tissues for effective operation.

An action potential (AP) is a brief electrical signal that travels through an excitable cell (neuron, cardiomyocyte, smooth muscle cell, or muscle fiber) and is typically caused by an external stimulus that depolarizes the cell membrane [1,2]. Cell membranes contain voltage-gated ion channels that allow the transfer of ions like sodium, potassium, and calcium across the cell membrane. Rapid depolarization, followed by a slightly slower repolarization of the cell membrane, results in an action potential, which is the fundamental electrical signature of the cell [1,2].

Electrophysiological mechanisms are essential for the proper functioning of the majority of the organ systems, including the cardiac, nervous, gastrointestinal, and the urinary systems, with AP propagation being the fundamental component of each system [3,4]. APs are essential for the nervous system's information transmission processes because they allow neurons to communicate with one another and with muscles. Several factors, including the width of the axon and the degree of myelination of the neuron, can influence the speed and strength of these signals [3,4]. Electrophysiological studies of the nervous system are used to measure the activity of individual neurons or populations of neurons. Electroencephalography (EEG) and magnetoencephalography (MEG) are the primary non-invasive tools that can be used to measure electrical activity in the brain and provide insight into brain function and dysfunction. These methods are commonly used to diagnose and manage epilepsy, sleep disorders, and other neurological conditions [5–8].

Similarly, APs in the cardiac system control the rhythmic contractions of the heart. The sinoatrial (SA) node, the heart's intrinsic pacemaker, initiates the action potential which is transmitted to the atrioventricular (AV) node and Purkinje fibers in the bundle of His which ultimately results in the coordinated contraction of the atria and ventricles [9]. The performance of the cardiac conduction system is evaluated using electrophysiological studies, which are used to diagnose irregularities in heart rhythm. Arrhythmias, a significant source of morbidity and mortality, can be diagnosed and treated using methods like electrocardiography (ECG) and intracardiac electrophysiology studies [10].

The study of electrophysiology and APs is critical for the detection and management of a wide range of diseases such as cardiovascular arrhythmias, seizures, Parkinson's disease, multiple sclerosis, neuropathies, gastric arrhythmias, and neuro-muscular disorders. While great advances have been made in electrophysiological mapping techniques that have aided in diagnosis and treatment, as well as enhanced our understanding of the human body, it is not without limitations. One of the challenges is precisely mapping tissue electrical activity in order to comprehend the underlying pathophysiological mechanisms. Another limitation is that few electrophysiological studies are invasive and necessitate specialized equipment and expertise, which limits their availability and practicability in certain clinical settings [11,12]. Furthermore, interpreting electrophysiological data can be challenging and may require specialized training [13–15].

Electrophysiological research is increasingly being prioritized in the diagnosis and treatment of a wide range of disorders. With the advancement of technology, newer electrophysiological techniques have been developed, resulting in more accurate and detailed measurements of electrical activity in the body.

Electroencephalography (EEG), for example, while important for understanding brain function and dysfunction, can only detect activity of the brain's outer layer and cannot detect the activity of the inner brain [5]. Patch-clamp recording is a significant development in electrophysiological research to investigate the behavior of ion channels in intact cells. While it allows for the high-resolution recording of ion channel activity, it is limited to studying only one ion channel at a time [16]. Electrogastrography (EGG) is a non-invasive test that records the electrical activity of the gastrointestinal system and is frequently used to

identify gastric arrhythmias [17,18] (as illustrated in Figure 1). Similarly, urodynamic studies can be used to assess urinary system function and diagnose urinary incontinence [19]. Yet, these techniques are high-cost and require complex signal processing [11,12].

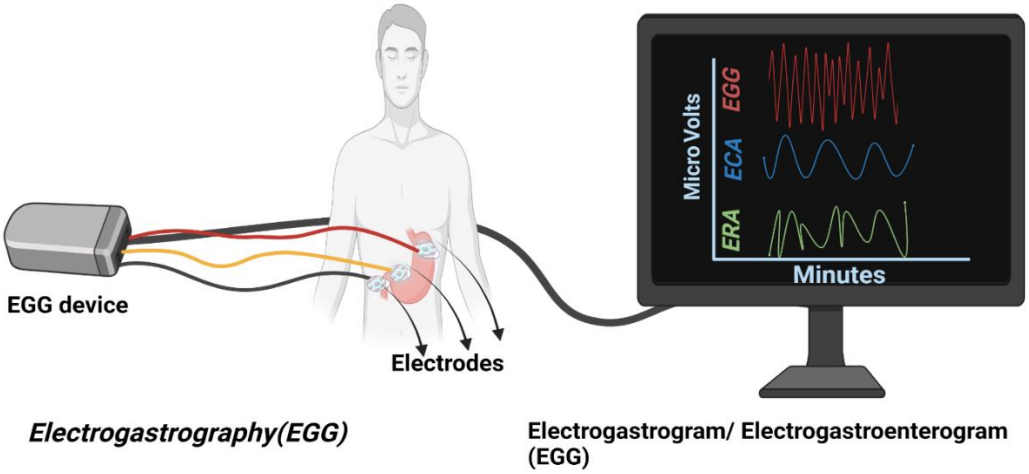

Figure 1. Showing the electrogastrogram measurement (Biorender.com). ERA—electrical response activity, ECA—electrical control activity, EGG—electrical gastrogram.

To summarize, recent EP studies have provided important insights into the electrical activity of the cells and organs in the body, but they are not without limitations. When interpreting the results of electrophysiological studies, it is critical to understand these limitations and to consider other factors that may influence electrical activity in the body [3]. Further research is needed to develop new techniques that can overcome these limitations and provide more detailed and accurate measurements of electrophysiological activity.

A potentially effective method for mapping EP involves utilizing microwaves to measure the electrical characteristics of tissues [20]. Microwaves penetrate tissues and interact with the water molecules within, which have varying electrical properties depending on the type of tissue and measure the dielectric properties of biological tissues such as conductivity and permittivity [21,22]. The initial database on dielectric properties, compiled in 1996 based on dielectric measurements at frequencies ranging from 10 Hz to 20 GHz, has gained greater attention in the research domain of non-ionizing radiation. Microwaves use non-ionizing electromagnetic radiation that transmit waves of electrical and magnetic energy at different frequencies, with a wide range of applications within and beyond the medical field [21].

Understanding the dielectric properties of healthy and diseased tissues is critical when diagnosing various diseases. The physiological condition of the tissue influences the dielectric properties of the biological tissue, which serve as an essential parameter for the electromagnetic modeling of the human body [21,23]. Tissue dielectric properties change due to changes in water and protein content, as well as cell type and structure [24]. Several studies have found that the amount of water in healthy and pathological tissues varies [22,25–27]. Meaney et al. and Kaufman et al. found that the electrical properties of benign and cancerous breast epithelial cells differ, and that the permittivity and conductivity of breast cancer are much higher than those of healthy tissues. Adipose tissue, which makes up most of the normal breast tissue and has lower water content and dielectric characteristics than benign tumors or malignant breast cancer, contributes to this in part [28,29]. This variation influences permittivity and conductivity, which can be measured with microwave techniques [25]. Understanding the dielectric properties of different tissues is critical for dosimetry (safety studies performed to calculate and assess the ionizing radiation dose absorbed while using wireless communication devices or undergoing radiological imaging) as well as implementing new electromagnetic (EM)-based technology [23,30]. Following technological

advancements, a wide range of applications have been proposed, such as the diagnostic applications of microwaves, which include, microwave imaging (MWI), microwaves in diagnostic pathology, microwave-based molecular diagnostics, dielectric spectroscopy, and therapeutic applications like microwave ablation [31]. By measuring the dielectric properties of different tissues using microwaves, researchers can obtain information about the electrical activity of cells within the body. For example, researchers have used microwave measurements to map the electrical activity of the heart, brain, and muscles [32–35]. Unlike other techniques such as catheterization, microwave measurements do not require the insertion of a probe into the body [36]. This makes the technique safer and more comfortable for the patient.

In this review paper, we discuss the basics of cellular EP of the cardiac, gastrointestinal, and nervous systems as well as the current state of the art in EP mapping methods. We summarize the potential use of the microwave technology in measuring the dielectric properties of these systems to augment medical diagnoses. Furthermore, we address the future perspectives for integrating EP studies with microwave technology and dielectric imaging to provide novel pathophysiological insights.

2. Materials and Methods

A thorough search of several databases, including Google Scholar, PubMed, and UpToDate, was conducted without language or time constraints. The search terms for tissue dielectric properties and microwave applications were "(microwaves, dielectric properties, dielectric spectroscopy, microwave ablation OR microwave imaging OR microwave energy)". Search terms for electrophysiology included "(Action Potential OR Electrophysiology of Cells)" AND "Cardiovascular Electrophysiology" AND "Enteric Electrophysiology" AND "(Electrophysiology of Nervous System, Electrophysiology of Seizures)"AND "Electrophysiology of Parkinson's Disease" AND "Electrophysiology of Other Systems" AND "Electrophysiology of Skeletal Muscle" AND "Optical Electrophysiology". The search for relevant literature focused on how microwave energy is used in electrophysiology mapping for therapeutic and diagnostic purposes. The keywords "(cardiac ischemia OR cardiac arrhythmias OR catheter ablation OR cryoballoon ablation OR dielectric mapping in heart OR KODEX-EPD OR seizures OR GI motility disorders, Gastroparesis) AND microwaves" were used as search criteria. To find recent developments in electrophysiology, the following search terms were used: "(electroencephalogram, electrocardiogram, electrogastrogram, electrophysiology advancements, electromyography, patch clamp technique)". The search terms for the applications of AI included "(machine learning OR artificial intelligence)".

3. Cardiovascular System

Abnormal cardiac rhythms, arrhythmias, are the leading cause of sudden cardiac death in the United States, with ventricular arrhythmias claiming about 450,000 lives annually, and atrial arrhythmias affecting over 2 million people [37].

A fundamental understanding of the electrophysiology of the heart is crucial in comprehending the mechanisms underlying various cardiac arrhythmias.

The regulation of cardiac electrical activity is mainly governed by intracellular and extracellular movement of Ca^{+2}, Cl^{-}, K^{+}, and Na^{+} [38]. The duration of the cardiac AP from the depolarization to repolarization phases is referred to as the action potential duration (APD) which normally ranges from 200 to 400 ms [39]. The electrical activities of the heart and changes in action potential can be recorded with the help of surface electrodes in the form of an electrocardiogram (ECG). The ECG exhibits the complete cardiac cycle through P, QRS, and T waves, where P represents atrial depolarization, QRS represents ventricular depolarization, and T wave represents ventricular repolarization [40]. Heterogeneities in the APD and abnormalities in the movement of ions across the cell membrane leads to cardiac arrhythmias [41]. Arrhythmias are mainly classified based on their site of origin, namely, atrial, and ventricular arrhythmias. Atrial fibrillation (AF), atrial flutter (AFL), and paroxysmal supra ventricular tachycardia (PSVT) are most prominent atrial arrhythmias,

whereas ventricular fibrillation (VF) and ventricular tachycardia (VT), which are known to instigate sudden cardiac death, constitute the most significant mortality risk [42].

3.1. Cardiac Conduction Disorders

AF occurs due to abnormally fast (100–175 beats/min) and uncoordinated atrial contractions and is the most prevalent type of arrhythmia affecting more than 33 million people globally [43]. AF is triggered most commonly by the ectopic beats originating from the pulmonary vein ostia [43], and is maintained by the reduction in APD which allows for the re-entry of stimulus through an arrhythmogenic substrate within atrial myocytes [44]. Similarly, AFL occurs due to the formation of a macro re-entrant circuit around the tricuspid annulus anteriorly and vena cavae orifices posteriorly with cristae terminalis as a functional barrier [41,45,46]. The two main types of PSVTs, atrioventricular nodal re-entrant tachycardia (AVNRT) and atrioventricular re-entrant tachycardia (AVRT), are also re-entrant arrhythmias; however, they differ in the location of re-entry circuits [47,48]. AVNRT occurs due to coexistence of a fast AV nodal pathway with a slow AV nodal pathway in the AV node. Here, the re-entrant circuit activation occurs near the posterior region of tricuspid annulus and the slow nodal pathway acts as arrhythmogenic foci. In AVRT, an accessory atrioventricular bypass tract is formed which functions as one appendage of the re-entrant circuit and leads to the premature excitation of ventricular myocytes [47,48]. The reduction in APD and the pre-excitation of atria due the re-entrant circuits manifests either as fibrillary waves with indistinguishable P waves, narrow QRS complex and irregular R-R interval (AF), or as a 'saw tooth' pattern due to the absence of distinct P waves with regular R-R intervals (AFL) on the ECG [49,50].

Ventricular arrhythmias are due to the unsynchronized, abnormally fast electrical activity of ventricular myocytes which can lead to sudden cardiac death and results in the loss of more than 300,000 lives each year [51]. VT/VF occur most commonly after myocardial infarction due to the heterogeneity caused by scar tissue within the ventricular wall, resulting in reduced APD favoring re-entry [52]. In ventricular arrhythmias, the aberrant electrical activities due to change in ionic movements are recorded as fibrillary waves without any identifiable P waves or QRS complex on the ECG [53].

3.2. The Current State of the Art in Cardiac EP Mapping

Over the decades, several methods have been developed to study cardiac EP for identifying and mapping arrhythmias; however, there remain several technical challenges to overcome. Even though the ECG is the oldest modality that helps in the identification of arrhythmias via changes in P, QRS, and T waves, it only reflects aggregate body surface electrical activity [54]. Additionally, it fails in assisting in the localization of arrhythmogenic foci [54]. Subsequently, various attempts were made to map the arrhythmias at intracardiac levels. Multi-electrode ("Basket") catheters record local activation recovery intervals and the data obtained are reconstructed as 3D color coded maps which help in identifying the origins of arrhythmias, but due to their low-quality resolution, precise data on re-entrant circuits cannot be obtained [55]. Furthermore, intracardiac mapping is unable to distinguish between atrial and ventricular systole and in mapping early diastole. In addition, the quality of virtual electrograms becomes compromised at a distance of more than 4 cm from the multi-electrode array [55].

Arentz et al. identified the pulmonary vein as the origin of ectopic beats using high resolution 3D mapping; however, difficulty in mapping the micro-entry of the circuit through the epicardial surface and the missed entry or exit of impulses through the re-entry circuits were limitations of this system [56]. Similarly, Wang and colleagues and Yoram Rudy performed a series of catheter-based EP studies to elicit the intricacies of the patterns of ventricular arrhythmias like VT and premature ventricular complexes [54], and the origin of the re-entry circuit in the atrial wall in atrial flutter and Wolff–Parkinson–White (WPW) [57], respectively. Although this ECGI imaging system provided high resolution images of electrical activation sequences with respect to the atrial and ventricular

surface, it could only map arrhythmic activities during the QRS complex, and it failed to map the endocardial circuit accurately during epicardial activation [54]. More recently, Tsyganov et al. used non-invasive epicardial and endocardial EP system (NEEES) to map and categorize ventricular arrhythmias in patients with non-ischemic and ischemic cardiomyopathy. This system could not map arrhythmias for both ventricles simultaneously and provided information on all types of arrhythmias, even clinically insignificant ones. Thus, the data obtained could not be used to devise a targeted ablation strategy [58]. An advanced method to visualize 3D electrograms would need to be superior in mapping arrhythmogenic substrates in atrial and ventricular tachycardia to traditional 3D mapping systems, as well as map the VT originating from the Bundle of His–Purkinje system [59].

Recently, Tung et al. attempted to outline a 3D model of VT with the help of concurrent epicardial and endocardial mapping [60]. This method facilitated the identification of arrhythmogenic foci existing within the isthmus or mid-myocardial region responsible for re-entrant VT. However, the employment of this method in routine practice is not feasible because of its shortcomings such as its difficulty in achieving accuracy in the mapping of the whole cardiac circuit and its lack of the adjoining region of isthmus as potential arrhythmogenic foci [60].

Previously, a non-fluoroscopic electroanatomical cardiac mapping system (CARTO) was utilized to map and ablate ventricular arrhythmias [61]. While this system facilitated the mapping of focal tachycardias such as idiopathic left VT, it required high clinical expertise to interpret the 3D map in one specific rhythm, as the mixing of rhythms can present false information of location of arrhythmogenic foci [61].

3.3. Potential of Microwave-Based Mapping of Cardiac EP

There is a need for a more accurate, patient-friendly, cost-effective, and non-invasive modality for mapping arrhythmias, as current systems have significant drawbacks. Dysfunction in cardiac EP is the underlying mechanism for all arrhythmias, and the dielectric properties of the heart are determined by its ionic composition and the water content of the tissues [32]. Therefore, diagnosing EP disturbances may be possible by studying changes in the heart's dielectric properties at microwave frequencies. Niko Istuk et al. performed a study to identify the dielectric properties of the six different regions of the ovine heart at microwave frequencies [33]. They employed Cole–Cole and Debye models to analyze the dielectric properties of the epicardium, endocardium, myocardium, pulmonary artery and vein, aorta, superior vena cava, and exterior and interior surface of both atrial appendages. The team concluded that with regard to dielectric properties, the heart should be considered a heterogeneous organ as each part exhibited different properties with a difference of up to 25%. The dielectric permittivity ranged from 44.18 to 56.68 and conductivity ranged from 1.64 s/m to 2.10 s/m [33].

As we have seen, along with changes in phases of action potential and refractory period, the different types of arrhythmias vary in their origin of arrhythmic foci. Taking a cue from the above study, we can propose that detecting the changes in the dielectric properties of different regions of the heart using microwaves can aid in diagnosing different types of arrhythmias. Currently, microwave-based imaging of dielectric properties is used as guidance for arrhythmia diagnosis and therapeutic procedures, such as catheter ablation and medical device development. These developments highlight the possibility of combining EP and microwaves to diagnose arrhythmias that are caused by disturbance to electrical properties that underlie effective conduction.

3.4. The Use of Microwaves for Catheter Ablation

Catheter ablation, to date, remains the primary treatment for arrhythmias [62]. Previously, distinctive electrograms and fluoroscopy were used to locate the slow pathway (SP) for ablation; however, these techniques carry the risk of recurrence and AV block [62]. Lei Ding et al. introduced a novel approach to visualize the endocardium with an enhanced resolution with the help of a wide-band dielectric system (KODEX-EPD). This system used

a 3D flattened panoramic view (PANO View) which allowed for the precise localization of SP and para-SP regions and improved the efficacy of SP ablation with reduced complications [62]. Before this study, Abeln et al. also proposed the potential of dielectric imaging for the identification of arrhythmic foci using the KODEX-EPD system [63]. More recently, Thomas Fink et al. performed a study to confirm the efficacy of KODEX-EPD system-guided ablation in patients with AF. They concluded that the ablation procedure was successful in these patients with no incidence of recurrence [64].

Cryoballoon ablation (CBA) for pulmonary vein isolation (PVI) is the most recommended treatment modality for AF due to the ectopic beats generated by PV [65]. However, despite PVI, patients with arrhythmias often suffer from AFL or tachycardia and require additional ablation later. In a study conducted by Pongratz et al., it was shown that a 3D Wide-Band Dielectric Imaging System (3D-WBDIS) served as a useful tool in successfully achieving CBA and mapping and the ablation of additional arrhythmias in a single procedure. This system eliminated the need for direct catheter–tissue contact and significantly reduced patient exposure to radiation [65]. The dielectric mapping system (KODEX-EPD/3D-WBDIS) also helped in eliminating the use of contrast during CBA [66]. In the study [66], saline solution was used instead of IV contrast to determine cryoballoon PV occlusion. The dielectric mapping system could still sense the alterations in the electric field in the proximity of catheter electrodes with precision. This modification can make CBA feasible in patients with renal insufficiency and contrast allergies [66].

While analyzing scar tissues in VF, the progressive changes in tissues during ischemia were observed to be in direct correlation with alterations in the electrical impedance of the cardiac tissues measured during ischemia [67,68]. M. Schaefer et al. conducted studies [69,70] to assess the dielectric spectrum of cardiac tissues in ischemia. These studies observed that the dielectric permittivity of the heart was increased after artificially induced ischemia [69,70]. The postulated reason behind this change was the closure of gap junctions within ischemic tissue resulting in alterations in the movement of ions. Furthermore, they observed that the stratified arrangement of myocytes in ventricular walls also affects the dielectric permittivity. The dielectric conduction was directly proportional to the number of cell layers affected [69]. Similarly, two consecutive studies performed by S. Y. Semenov et al. to analyze the change in dielectric properties during myocardial infarction (MI) in the canine heart [71,72] found that there was a significant difference in the dielectric permittivity of normal and infarcted tissues. Subsequently, on comparing an ischemic canine heart with a human left ventricular aneurysm caused by a decade-old MI, they found that the dielectric properties of both tissues were similar. Based on this observation, it was proposed that microwave spectroscopy can serve as a potential tool for physiologic imaging systems and can guide the ablation of the full thickness of scar tissue [71]. In addition, microwave radiometry can also facilitate the detection of plaques in atherosclerotic vessels by sensing electromagnetic radiation from vessels [31].

3.5. The Use of Microwaves in Cardiac Medical Devices

Cardiac pacemakers are one of the effective modalities available for the treatment of arrhythmias; currently, the most widely used pacemakers are implantables with a wired connection between cardiac chambers and subcutaneous implants [73]. In a study conducted by Awan et al., an attempt was made to design a leadless pacemaker by utilizing the dielectric properties of the heart. These properties were sensed by industrial, scientific and medical (ISM), and ultra-wide band (UWB) waves and were successfully transmitted to subcutaneous implants [73]. Previously, A. J. Johansson also performed a study to assess the efficacy of microwaves to sense the recordings from implanted pacemakers using circumference antennae [74]. Additionally, the utility of microwaves in heart rate monitoring for diagnosing AF, blood pressure monitoring for hypertension [75], and sensing inputs from implantable and ingestible medical devices for diagnostic and therapeutic purposes were also explored [76]. Thus, there is compelling evidence to suggest that microwave-based mapping of EP has the potential to greatly improve the accuracy and effectiveness

of arrhythmia diagnosis and treatment, while reducing costs and invasiveness. Therefore, the widespread use of the microwave-based imaging of dielectric properties should be explored as a promising diagnostic and therapeutic tool for abnormalities in cardiac EP.

4. Nervous System

According to the Global Burden of Diseases, neurological diseases are the leading cause of disability-adjusted life years (DALYs) and the second leading cause of death globally. The number of deaths from neurological diseases increased by 36.7% between 1990 and 2015, while the number of DALYs increased by 7.4% [77].

A neuronal action potential comprises depolarization, repolarization, and hyperpolarization stages. In neurons, depolarization is triggered by the opening of voltage-gated sodium channels (Nav) in the plasma membrane, followed by repolarization mediated by the opening of voltage-gated potassium channels (Kv) [78]. It is at the axon hillock where the action potential initiates, but in sensory neurons, it initiates at the distal terminal of the axon due to a higher density of Nav receptors [78]. In myelinated axons, action potentials propagate through saltatory conduction resulting in faster conduction, compared to unmyelinated axons, where the action potential propagates as a continuous wave of depolarization [78].

4.1. Neurological Disorders

Epilepsy is a common neurological disorder characterized by recurrent seizures resulting from abnormal electrical activity in the brain [79]. The electrophysiological hallmark of seizures on the EEG is the presence of epileptic discharges, which are classified as interictal and ictal [80]. The EP of seizures is complex and involves several different mechanisms that can result in abnormal neuronal activity in the brain, including altered neuronal excitability, abnormal synaptic transmission, and changes in ion channel function, particularly voltage-gated ion channels such as sodium, calcium, and potassium channels [81–83]. Understanding these mechanisms is critical for developing effective treatments for epilepsy and improving the management of seizures in affected individuals. Parkinson's disease (PD) is a neurodegenerative disorder that affects the basal ganglia, resulting in dopaminergic deprivation due to neuronal loss in the substantia nigra pars compacta. It presents with both hypokinetic and hyperkinetic symptoms, which are believed to be caused by electrophysiological abnormalities [84]. Deep brain stimulation (DBS) is a neurosurgical technique that involves implanting electrodes in specific areas of the brain to deliver electrical stimulation, with the aim of modulating neural activity and treating a range of neurological conditions, including PD [85]. DBS has shown efficacy in improving motor symptoms and quality of life in advanced PD [86]. However, it is typically reserved for patients who are unresponsive to medication, and not all patients are eligible for the surgery. Furthermore, there are potential adverse effects associated with DBS, such as infection, bleeding, and hardware malfunction, and a risk of cognitive and psychiatric side effects [87]. Future research may be required to refine and improve the technique, potentially expanding its applicability and effectiveness in treating PD. Peripheral neuropathies result from damage to the peripheral nervous system and present with a wide range of symptoms such as numbness, tingling, weakness, and pain. The pathophysiology and EP of neuropathies can vary depending on the underlying cause of the nerve damage [88,89]. In general, the pathophysiology of neuropathies involves damage to the myelin sheath resulting in slowed or blocked nerve impulses [90] or axon of peripheral nerves, which can cause nerve impulses to become weaker or fail altogether. Axonal damage is typically associated with a more severe form of neuropathy and can be caused by a range of factors, including toxins, infections, and autoimmune disorders [91,92].

4.2. The Current State of the Art in Neuronal EP Mapping

There are various types of EP tests for the nervous system that can be used to study epilepsy, Parkinson's disease, and neuropathies, as well as psychiatric disorders such as

depression and thought disorders [93]. EEG is a common technique used to record electrical activity in the brain and is helpful in diagnosing and localizing epileptogenic foci [79,94,95]. EEG is slightly more reliable than MRI in lateralizing temporal epilepsy and can detect high-frequency oscillations associated with epileptogenic tissue [80,96].

MEG is another non-invasive tool that accurately localizes sources of epileptiform discharges using magnetic fields, providing 3D mapping of epileptiform activity to structural and metabolic anatomy [97]. However, MEG has limitations in accurately locating the origin of seizures and is less sensitive to deep brain structures such as the hippocampus and amygdala [98]. Its availability is limited due to high cost and the need for specialized personnel [99], and it is susceptible to movement artifacts [100].

Functional magnetic resonance imaging (fMRI) is a non-invasive technique that measures blood flow changes in response to brain activity, making it useful in identifying brain regions activated during seizures and studying functional connectivity in epilepsy patients. EEG-linked fMRI can produce functional MRI images that show the location of focal increases in blood flow corresponding to EEG spikes, potentially obviating the need for invasive recordings in some cases [101].

When non-invasive methods fail to locate the source of epileptic activity, an invasive procedure like intracranial electroencephalography (iEEG) is used. It involves placing electrodes directly on or within the brain to provide high spatial and temporal resolution. Invasive monitoring is recommended for patients with multifocal seizure onsets, discrepant EEG and MRI findings, or neurodevelopmental issues. iEEG is particularly useful in identifying epileptogenic regions that encroach upon language cortex and in assessing the extent of the epileptogenic lesion [101,102]. Wide bandwidth intracranial EEG, recently discovered to be a possible biomarker of epileptogenic brain, has shown that interictal high-frequency oscillations are preferentially localized to the brain region causing spontaneous seizures [103].

With recent advancements, a novel diagnostic modality, 7T MRI, allows for the improved visualization of brain structures and better detection of subtle abnormalities in epilepsy patients that are frequently missed on standard MRI [104]. It also provides better mapping of eloquent cortical regions and white matter tracts critical for surgical planning. However, limitations include image distortions, limited accessibility, the potential for increased radiofrequency power deposition in the brain, and incidental findings that could lead to unnecessary testing and anxiety [105–107]. Using multiple techniques in combination is necessary for a more complete understanding of brain function.

EP testing, such as nerve conduction studies (NCS) [108] and electromyography (EMG) [108], can help diagnose and characterize neuropathies by measuring nerve impulses and muscle activity [109]. However, EP studies have limitations in detecting pilot stages of neuropathy and localizing nerve damage. Other tests, such as quantitative sensory testing (QST) and autonomic testing, may also be used but have their own limitations such as subjectivity and complexity [110]. Therefore, a comprehensive diagnosis and treatment plan for neuropathies should involve a combination of EP testing, other diagnostic tests, and clinical evaluations.

The patch clamp technique is a powerful tool for studying the electrical properties of cells, particularly in the nervous system. It has been used to investigate different cell types and intracellular organelles. The technique allows for the observation of changes in the conductance of ionic channels in real-time, providing detailed insight into their regulation and function. Ligand-gated channels are important targets for pharmacological agents used in treating neurological and psychiatric disorders. The patch clamp technique has therapeutic implications for several pathological conditions, including cystic fibrosis, Lambert–Eaton syndrome, hyperkalemic periodic paralysis, amyotrophic lateral sclerosis, Alzheimer's disease, and diabetes mellitus [16].

4.3. Potential of Microwave-Based Mapping of Neuronal EP

The increasing burden of electrophysiological disorders highlights the need for better diagnostic modalities to map the EP of the nervous system. Microwave technology has potential applications in the diagnosis and treatment of electrophysiological disorders of the nervous system. It has been explored as a means to investigate the electrical properties of neurons and monitor changes during physiological processes [111,112]. Microwave imaging techniques, such as microwave tomography, can create a 3D image of tissue and study its electrical properties [113,114]. Studies have shown that microwave-based imaging techniques have shown effectiveness in detecting and locating damaged tissues caused by medical conditions or injuries, including ischemic or hemorrhagic brain strokes. Additionally, these techniques can be utilized to detect changes in brain tissue conductivity during seizures and accurately localize seizure onset zones in patients with epilepsy [115–117]. These findings highlight the potential of microwave-based imaging as a valuable tool for both detecting brain damage and accurately localizing seizure onset zones in individuals with epilepsy. Additionally, microwave therapy has shown promise as a non-invasive approach to treating neuropathies, particularly diabetic neuropathy [118,119]. However, further research is needed to fully understand the potential uses of microwave technology in clinical practice for the diagnosis and treatment of electrophysiological disorders.

Similarly, microwaves have potential uses in improving DBS therapy. For instance, a study explored the use of microwave ablation for the selective destruction of brain tissue in the target area of DBS, which could potentially improve the efficacy of therapy [120]. Additionally, microwaves have been investigated for their potential use in wirelessly powering the implanted DBS devices [121]. These studies suggest that microwaves have potential uses in improving DBS therapy, including improving targeting precision and the wireless powering of the implanted devices. However, further research is needed to fully understand the safety and effectiveness of these approaches in clinical settings.

5. Gastrointestinal System

The gastrointestinal tract comprises a variety of electrically excitable cells with underlying similar principles of electrophysiology [122]. The two fundamental electrical activity patterns across the smooth muscle cells, namely, slow waves and spike potentials, lead to coordinated contractions of smooth muscle, which forms the basis of normal gastrointestinal motility [122]. Gastrointestinal (GI) disorders are one of the major contributors to healthcare expenditure around the world [123]. Out of these, GI motility disorders account for 30–45% of all GI disorders worldwide, affecting about 30 million Americans [124].

The GI tract has specialized pacemaker tissue and conduction pathways like the heart, with interstitial cells of Cajal (ICC), located in the myenteric plexus (ICC-MY), that generate slow electrical waves propagating through smooth muscle layers [122]. The gastric myoelectrical activity includes slow waves or pacemaker potential, also known as electrical control activity (ECA), generated by ICC [3,125,126], analogous to the SA node of the heart [122], and spike potentials, also known as electrical response activity (ERA) [17,127,128], reflecting gastric peristalsis. Both can be detected via EGG [127,129]. The normal discharge rate in the GI tract varies depending on the organ, ranging from 5 to 8 bpm for the greater curvature of the stomach to 12 bpm in the duodenum, decreasing to 8 bpm in the ileum [122]. The migrating motor complex (MMC) occurring in the stomach and small intestine is a cyclic recurring motility pattern during fasting and is interrupted by feeding [130]. The absence of MMC has shown to be associated with various GI disorders including gastroparesis, small intestinal bacterial overgrowth, and intestinal pseudo-obstruction [130]. In the GI tract, two types of movement take place, namely, peristalsis and segmentation. Peristalsis occurs due to involuntary contraction and relaxation of the circular and longitudinal muscles, which allows for the propulsion of food contents from the pharynx to the anus, whereas segmentation helps in mixing the food contents. Both activities play a vital role in the absorption of water and nutrients [131].

5.1. Gastrointestinal Disorders

The myoelectrical activity of the stomach may become abnormal due to diseases, on stimulation, or spontaneously and include gastric dysrhythmia, abnormal slow wave propagation, and electro-mechanical uncoupling [17]. EGG recordings have shown that the typical range of gastric electrical activity (normogastria) is 2–4 cycles per minute (cpm), whereas the range of abnormally low frequency known as bradygastria (slow pacemaker) or high frequency known as tachygastria (fast slow waves) is 0.5–2 cpm and 4–9.00 cpm, respectively [17,127].

The disruptions in the electrical activity of the GI tract lead to GI motility disorders like gastroparesis, achalasia, gastroesophageal reflux disease (GERD), functional dyspepsia, unexplained nausea and vomiting, irritable bowel syndrome, slow-transit constipation, and Hirschsprung disease [122,132]. GI motility disorders are a cause of significant morbidity, but unlike cardiac arrhythmias, are not typically life-threatening [132]. However, diagnosing these disorders is often challenging, as they can be difficult to differentiate from mechanical obstruction, which leads to unnecessary laparotomies [133]. Therefore, understanding the underlying arrhythmogenic mechanisms can provide insight into the pathogenesis of GI motility disorders and potential molecular targets for future therapy [124].

5.2. The Current State of the Art in Gastrointestinal EP Mapping

There are various EP tools to record GI electrical activity such as afferent fiber recordings, single-unit recordings, multi-electrode arrays, field potentials, patch clamping, voltage-sensitive dyes, and calcium reporters. These tools are used to study the properties of enteric neurons, enteric glia, ICC, dorsal root ganglion (DRG), spinal neurons, spinal glia, and neurons and glia throughout the brain to determine the primary pathophysiological mechanisms of GI disorders [134]. EGG is one such tool that measures gastric myoelectrical activity and can be used to identify gastric arrhythmias [17,127,135].

EGG is useful in understanding GI motility disorders and assessing the efficacy of gastroprokinetic agents, to evaluate the outcome of GI surgery [127]. It provides supportive evidence of gastric dysfunctions for other techniques like manometry and gastric emptying studies [136]. However, EGG has its limitations, such as the need for a quiet room to avoid distractions, stopping medication that might modify gastric myoelectrical activity [136], and motion artifacts [137,138]. There are also no standard recommendations for electrode placement, EGG recording length time, test meal, and the EGG systems and analysis, and discrepancies in the defined normal ranges vary among many investigators [136]. An array of electrodes is used in high resolution EGG, a breakthrough in this field, that can quantify both direction and speed of slow waves. Using it, spatial anomalies of gastric slow-waves can be recorded which go undetected during single-channel recordings [139]. Thus, an acceptable consensus was required to define abnormalities based on EGG recordings, and specialized instruments and expert interpretation of data are required, which could be challenging and may necessitate expert training [136].

Lately, it has been demonstrated that gastric electrical stimulation (GES) can effectively relieve the symptoms of gastroparesis [140]. GES modifies the intrinsic electrical activities of the stomach by stimulating it more frequently than the typical electrophysical frequency of 3 cycles per minute [141]. Either temporary endoscopic stimulation (Endo Stim) [142] or surgical implantation of a commercially available neuro-stimulator (Enterra-gastric pacemaker) that has been authorized by the FDA must be surgically implanted to achieve GES [143].

While producing promising results, gastric pacemakers have not been widely employed in clinical settings since they necessitate protracted implantation procedures or, in the case of Endo Stim, burdensome temporary wires that obstruct the patient's daily activities [143]. According to a study by Smitha et al., battery-based and battery-free wireless gastric stimulators were successfully constructed and characterized, which modulated the myoelectrical activity in the animal stomach [143]. This device also has drawbacks, like the fact that the gut is a much larger organ system than the heart, making it difficult to precisely

target power generation and delivery, as well as associated complications like infection, hemorrhage, neurostimulator migration, and allergic reaction to implanted material [144].

5.3. Potential of Microwaves-Based Mapping of Gastrointestinal EP

This high burden of motility disorders warrants the need for a more standardized, patient-friendly, inexpensive, and readily available diagnostic modality, which has given rise to the study of dielectric properties of tissues and the use of microwaves. Microwaves can be used as a promising tool to wirelessly record gastric electrical activity. A new tool has been developed that can record gastric electrical activity via three channels wirelessly and also deliver high-energy electrical pulses to the stomach and has been validated by animal experiments [145]. Two studies, one by Wang et al. [145] and the other by Berry et al. [146], utilized miniature-sized wireless systems to acquire and modulate gastric electrical activity. These systems implemented wireless power transfer and were used to explore the relationship between gastric dysrhythmias and functional GI disorders, as well as study the potential of electroceutical therapies for motility disorders in rodents [146]. Similarly, in future microwaves can be used to detect gastric electrical activity and for treating functional GI disorders. Ablation therapy, used for the successful treatment of cardiac arrhythmias, has also been recently translated to GI diseases [147]. Studies have shown that the radiofrequency ablation of gastric smooth muscles and ICC produce an electrical barrier, thus eliminating gastric dysrhythmic mechanisms [148,149]. Similarly, microwaves may be used for gastric ablation as a non-ionizing tool. Microwave imaging can be used to measure dielectric properties, which have been used to detect colon polyps, colon cancer [150], differentiate normal liver tissues from cirrhotic liver (stages S1 and S2), human hepatocellular carcinoma (well and moderately differentiated), liver hemangioma [151], and could potentially aid in the diagnosis of other GI motility disorders. Further research is needed to establish a database of the dielectric properties of the GI tissue during these different diseases which can help develop novel diagnostic and therapeutic tools.

6. Application of Microwaves for Mapping the EP of Other Systems

6.1. Musculoskeletal System

The electrophysiology of skeletal muscle involves the electrical activity that triggers muscle contraction via action potential along the motor neuron [152]. Electrophysiological disorders such as myasthenia gravis and muscular dystrophy affect the neuromuscular junction and proteins responsible for muscle structure, causing weakness and degeneration [153]. EP studies, like electromyography (EMG), measure muscle electrical activity with electrodes [154], but are invasive, uncomfortable, and have limitations such as susceptibility to fatigue, limited tissue coverage, and insufficient information on structural and biochemical changes [155]. A study conducted by Semenov et al. demonstrated the potential of microwave tomography in mapping the EP of skeletal muscles. The researchers used a microwave tomography system to measure the dielectric properties of a rat gastrocnemius muscle in situ abnormalities [156]. They found that the system was able to accurately detect changes in the muscle's electrical activity, indicating that it could be a useful tool for studying muscle function. Overall, understanding the electrophysiology of skeletal muscle and its disorders is essential for developing effective treatments and improving the lives of those affected by these conditions. Microwave imaging can help map the EP of skeletal muscles non-invasively, which can assist in the prevention and treatment of skeletal muscle atrophy and channelopathies.

6.2. Urinary System

The EP of the urinary system relies on the electrical activity of muscles and nerves to control the kidneys, ureters, bladder, and urethra [157]. In humans, peristaltic movement from the kidney to the bladder occurs at a rate of two to three contractions per minute, triggered by low-frequency waves from interstitial cells of Cajal (ICC) in the renal pelvis and proximal ureter [158]. Dysfunction of these cells can cause urological diseases such

as obstructive and non-obstructive hydronephrosis, vesicoureteral reflux, and overactive bladder (OAB) [159]. OAB, prevalent in 43% of females and 27% of males [160] is linked to the spontaneous contractility of the detrusor muscle mediated by interstitial cells and electrical signals from the ureter [161]. Electroanatomic and electromyographic mapping are the proposed methods for better understanding and treating these disorders [161,162]. The patch clamp technique is the most reliable method for investigating ion channels in the urethra [16].

Dielectric imaging methods could also be used to map electrophysiological pathways in the urinary system and localize triggers instigating abnormal peristalsis or other electrophysiological issues [163–165]. However, the use of microwave imaging for mapping the EP of the urinary system is still in the preliminary stages of development, and further research is needed to refine the technique and optimize its use for clinical applications.

6.3. Female Reproductive System

Myometrial smooth muscles are influenced by hormones, ionic movement, and drugs [35], which generate spontaneous electrical activity leading to burst and plateau pacemaker potentials [166,167]. The electrical activity of myometrium can be altered, resulting in poly systole, uncoordinated contractions, and tachysystole. Similar to cardiac tissue, fibrillatory wave and circus movements can also be observed in myometrial tissue [168]. Recent studies suggest the existence of ICC-like cells for pacemaker potential generation [169]. Mapping pacemaker location is challenging due to the limitations in current techniques such as multielectrode mapping [170,171], electromyography (EMG), and myomagnetography (MMG). Newer EP recording and mapping tools can improve maternal and fetal outcomes during childbirth [172]. Electrohysterography (EHG) recordings show promise in predicting preterm labor diagnosis based on propagation velocity, but the unknown pacemaker location in the myometrium limits its clinical utility [173].

Mapping the pacemaker location and observing wave propagation could allow for the modulation of its activity to improve maternal and fetal outcomes in clinical practice. This can possibly be achieved using microwaves. Microwave technology has been used for diagnostic and therapeutic purposes in the myometrium, the measurement of the dielectric properties of uterine fibroid (leiomyoma) [174], and the use of microwave ablation [175] for the treatment of leiomyoma highlights this concept. Similarly, microwaves can be used to study the dielectric properties of pregnant human myometrium to map the electrophysiological pathways. It can serve as a low-cost, non-invasive tool to monitor the propagation of myometrial waves and to differentiate between physiological contractions and true labor. Ultimately, these advancements could help provide newer targeted therapies to patients experiencing preterm labor.

6.4. Ophthalmology

The electrophysiology of the eye involves measuring the electrical activity of the retina and visual pathways using techniques such as electroretinography (ERG) and visual evoked potential (VEP) testing [176–178]. Other techniques used are electro-oculography (EOG) [179] and multifocal electroretinography (mfERG) [180]. These methods can diagnose EP disorders of the eye such as retinal dystrophies [181], optic neuropathies, and the vision problems due to epilepsy. Multiple sclerosis (MS) is one such disease-causing optic neuritis, with delayed P100 components upon VEP testing being a characteristic abnormality associated with the disease [182]. While these tests are painless and non-invasive, they still require electrode contact and stimulation with flashes of light, which can be challenging. Microwaves also offer promising diagnostic benefits in ophthalmology. They provide measurements of different tissue layers in the eye without direct contact [183]. A newer technique, microwave-induced thermoacoustic tomography (MITT), uses microwaves to measure the electrical activity of the eye and may be useful in the diagnosis and monitoring of glaucoma [184]. Further research should be conducted to use this microwave technology

in the diagnosis of the EP disorders of the eye and to understand its potential as well as to ensure safety.

7. Discussion

Studies have recently revealed that electrophysiology is not limited to so-called excitable cells but is prevalent in every single cell of the human body. The successful integration of electrophysiology and molecular biology results in an ionic channel structure–function analysis that identifies the molecular substructures responsible for permeation, selectivity of activation and inactivation, and several types of blocks. Future research may lead to the creation of more effective drugs to treat ionic-channel-dysfunction-related conditions as well as the genetic-engineering-based treatment of diseases like cystic fibrosis, Parkinson's disease, epilepsy, cardiac arrhythmias, ischemia, hypertension, and GI motility disorders [185].

Noteworthy progress has been made in the field of EP in recent years, with a variety of methods being created for mapping and measuring the electrical activity of different systems of the body. The use of microwaves for mapping EP has been gaining significant interest. This method has shown potential in several applications, including the mapping of the EP of the heart, brain, and GI tract, among others. The patch clamp technique and microwave technology have revolutionized the way scientists study EP. The patch clamp technique is a widely used EP method that enables the measurement of ion currents across cell membranes with high accuracy and resolution. The combination of patch clamp technique and microwave technology has the potential to provide new insights into the mechanisms of neural function and disease. The patch clamp technique has been traditionally used to study individual cells, but the combination of this technique with microwave technology as illustrated in Figure 2 can enable researchers to map the electrical activity of cells in real-time along with the dielectric properties. By combining multicellular arrays with microwaves, EP mapping might be possible over tissue areas. This will allow us to potentially map the changes in AP during arrhythmic processes by measuring the dielectric characteristics of the tissue and aid in locating t the source of origin.This can help us understand the dynamic interactions between cells and their roles in neural functions that leads to arrhythmogenesis.

As illustrated in Figure 2, simultaneous patch clamp and dielectric property measurement is warranted to develop a relationship at high temporal resolution. Current technologies for dielectric property measurement face challenges like not being able to measure the dielectric properties at the level of an individual cell due to the usage of rigid probes.Significant technological innovations are required for novel flexible probes that measure dielectric properties at high temporal resolution. These advances will open new avenues for applying dielectric properties as a novel biomarker for electrophysiology mapping using microwave imaging. Additionally, with artificial-intelligence-assisted microwave systems, mapping the APs of various tissues will allow for the precise localization of arrhythmogenic substrates, thereby facilitating patient-specific treatment strategies.

The use of microwave-based techniques for mapping the electrical activity of the heart has the potential to provide a non-invasive alternative to traditional invasive mapping methods, such as catheter-based mapping. One of the key benefits of this technique is its ability to provide real-time mapping of the heart, which can help in the diagnosis and treatment of various cardiac conditions, including arrhythmias and conduction disorders. There are currently several microwave-based techniques being developed for mapping cardiac EP, including microwave-based impedance imaging and microwave-based electrical impedance tomography. These techniques involve the use of microwave signals to measure the electrical properties of the heart, such as impedance and capacitance, which can provide a unique and valuable insight into the electrical activity of the heart. Similarly, an advantage of using microwaves for mapping neurological EP is its ability to provide a non-invasive method for measuring the electrical activity of the brain and nervous system. This contrasts with traditional invasive methods, such as electrodes implanted into the brain, which carry

the risk of infection and other complications. The use of microwaves for mapping EP is also being increasingly explored in the field of GI EP.

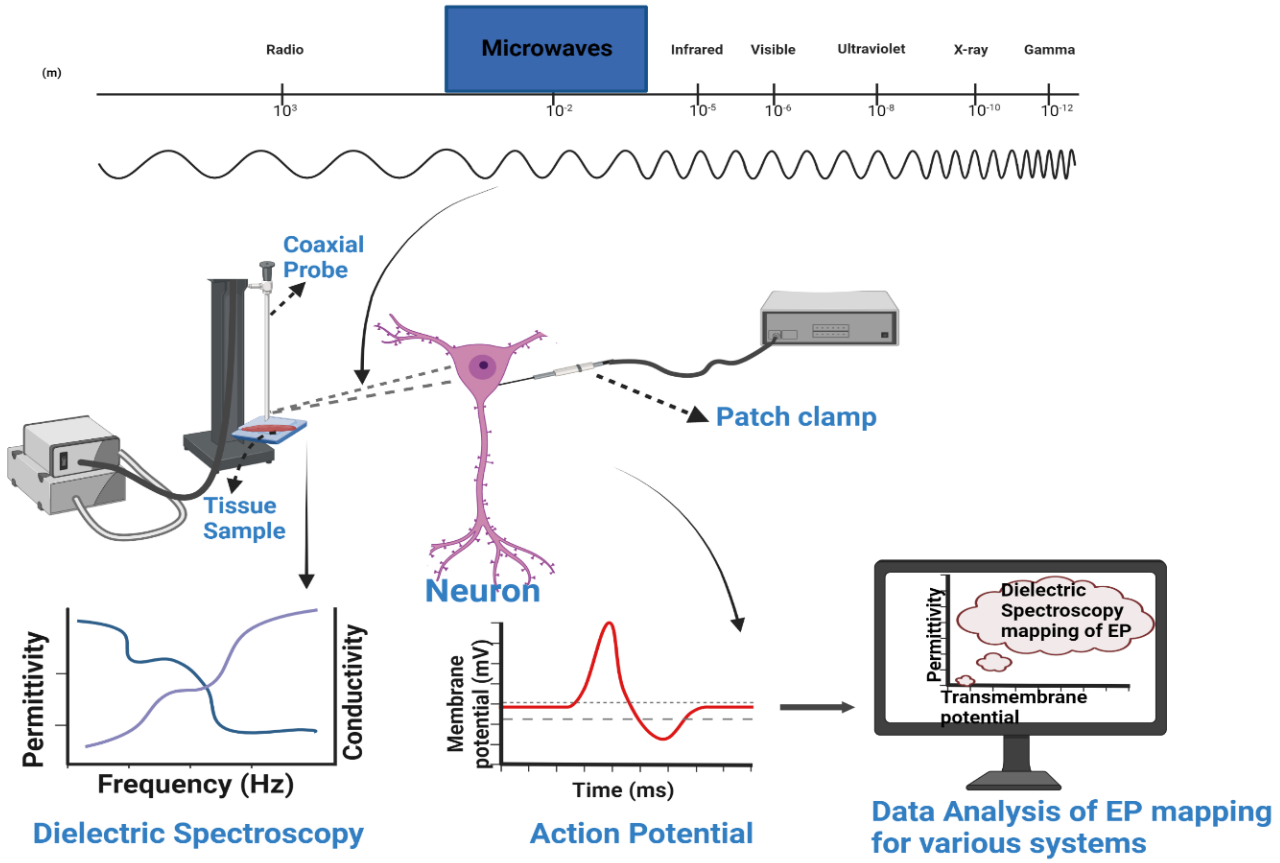

Figure 2. Illustration of mapping dielectric properties and action potentials at the molecular level to study the electrophysiology of various systems (Biorender.com).

As with cardiac EP, the use of microwaves for mapping neurological and GI EP is still in its pilot stages, and there are several technical challenges that need to be addressed, including the development of more sensitive and accurate sensors and the optimization of the algorithms used for data analysis. However, the potential benefits of this technique make it an exciting area of research, and the prospects for its use in EP are very promising.

The use of microwaves for mapping EP is not limited to just the cardiovascular, nervous, and gastrointestinal systems. There are also ongoing efforts to apply this technology to other systems of the human body, such as the musculoskeletal system, urinary system, ophthalmological, and female reproductive system. Figure 3 highlights the potential use of microwaves for imaging tissue from various physiological systems.

In the musculoskeletal system, the use of microwaves for mapping electrophysiology has the potential to provide new insights into the diagnosis of muscular disorders. By mapping the electrical activity of the musculoskeletal system, it may be possible to identify early signs of these conditions and develop more effective treatments. The electrical activity of the urinary system plays a vital role in the regulation of bladder function and the elimination of waste from the body. By mapping the electrical activity of the urinary system using microwaves, it may be possible to identify early signs of conditions such as urinary incontinence and provide more effective treatment strategies.

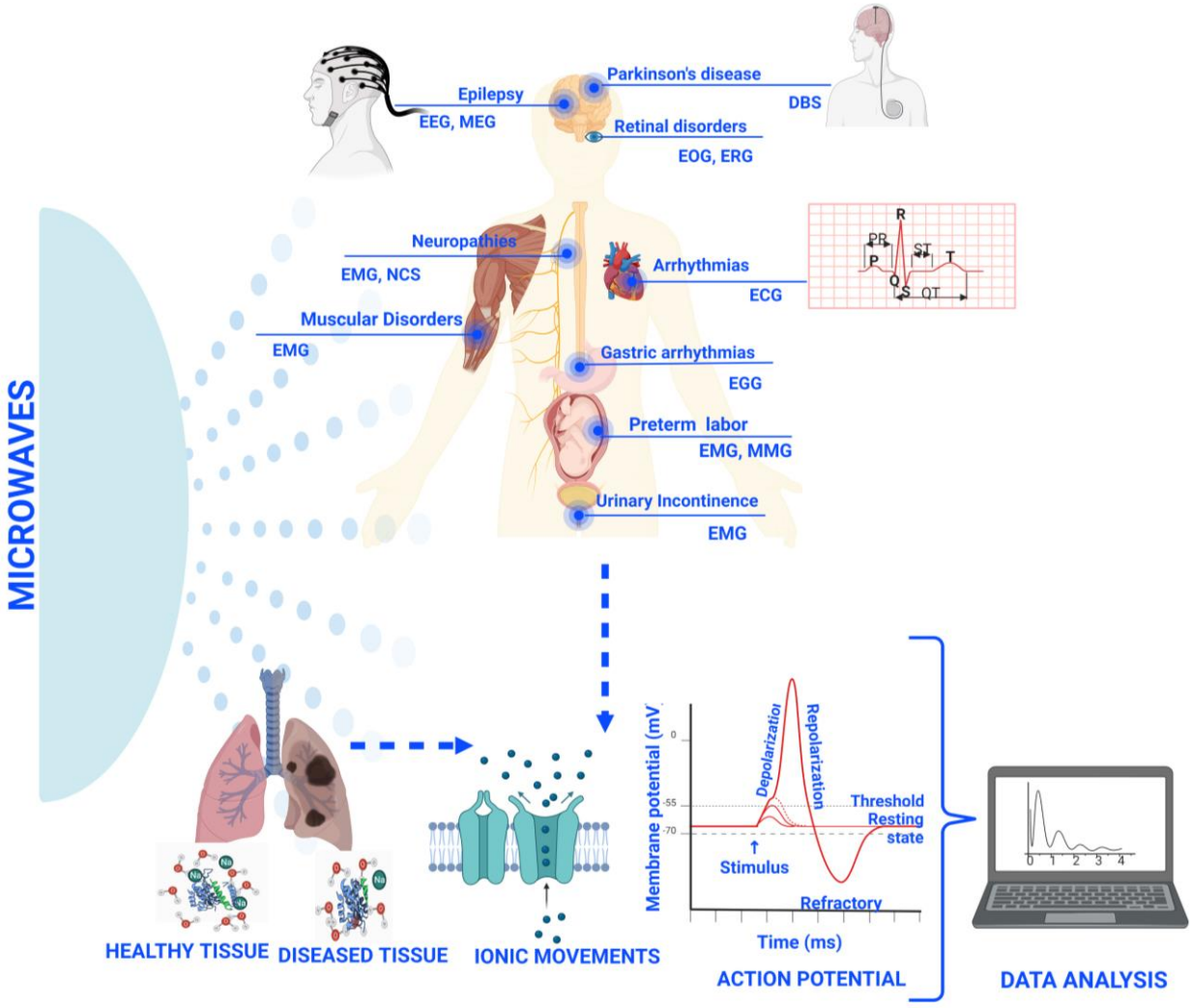

Figure 3. Pictorial illustration of how the dielectric properties of healthy and diseased biological tissues differ, as well as the use of microwaves in mapping the changes in action potential due to ionic movement changes, eventually assisting in mapping the electrophysiology of various systems. EEG—electroencephalogram, MEG—magnetoencephalogram, EOG—electrooculogram, ERG—electroretinogram, ECG—electrocardiogram, EGG—electrogastrogram, EMG—electromyogram, NCS—nerve conduction study, MMG—myomagnetogram (Biorender.com).

Microwave technology eliminates the need for electrode insertion or other invasive procedures. And, these non-invasive diagnostic methods offer a unique opportunity to detect physiological and pathological changes while requiring minimal sample handling [27]. This makes brain mapping a safer and more comfortable option for patients [186]. Microwave technology has been found to possess a remarkable spatial resolution, enabling it to detect even the slightest alterations in electrical activity within regions affected by myocardial ischemia, infarction, and breast cancer. This ability is akin to the detection of electrical activity in other parts of the body [187,188]. Because neurological diseases can be detected through subtle changes in electrical activity, this is critical for brain mapping. Microwave technology allows for the real-time monitoring of electrophysiology [189]. This real-time monitoring is especially critical in monitoring disease progression [190] and treatment response [191]. Although microwave imaging is a promising technology for mapping the electrical properties of tissues in clinical settings, safety concerns must be addressed to ensure patient safety [189]. Tissue damage is a potential risk if the microwave energy used for imaging causes heating that leads to burns or tissue damage. However, the use

of low-power microwave energy is typically controlled to prevent excessive heating, and studies have shown that exposure levels are below the threshold for tissue damage [192]. Furthermore, interference with other electronic devices is also a concern, but studies indicate that the microwave energy levels used for imaging are well below levels that can cause interference [193]. Overall, the risks associated with microwave imaging can be mitigated through appropriate control of the microwave energy used. In conclusion, microwave imaging is a promising technology that has the potential to significantly improve the diagnosis and treatment of various medical conditions [189].

Another intriguing aspect of the future of mapping EP with microwaves is the incorporation of machine learning techniques. Machine learning algorithms can be used to analyze enormous amounts of data generated by microwave-based EP mapping, assisting in the identification of patterns and trends that may not be visible to the naked eye. This can help to improve mapping accuracy and provide a more detailed and comprehensive understanding of electrical activity in various human body systems [194]. Furthermore, machine learning algorithms can be used to create predictive models for various physiological processes, such as the onset of certain conditions or disease progression [195,196]. This can help to improve patient outcomes by allowing for earlier detection and intervention. Furthermore, machine learning algorithms can be used to optimize the data analysis algorithms used in microwave-based EP mapping. This can help to improve the mapping process's accuracy and efficiency, resulting in faster and more reliable results [197].

8. Conclusions

The use of microwaves for mapping EP in various systems of the human body has shown great promise in recent times and is an exciting area of research. The ability to provide a non-invasive method for measuring the electrical activity of various systems in the human body provides a valuable and unique insight into the functioning of these systems. While there are several technical challenges that need to be addressed, including the development of more sensitive and accurate sensors and the optimization of the algorithms used for data analysis, the future prospects for the use of microwaves for mapping EP in various systems of the human body are very promising. This is a rapidly evolving field, and as technology continues to advance, it is likely that we will see further advancements and breakthroughs in the coming years. Furthermore, the integration of machine learning techniques into the field of mapping EP using microwaves has the potential to greatly enhance our understanding of various systems in the human body and improve patient outcomes. The prospects for this field are very promising, and it will be exciting to see how machine learning algorithms continue to shape and impact this area of research.

Author Contributions: A.S.S.C. and S.P.A. defined the review scope, context, and purpose of the study. A.S.S.C., V.K.M., B.B., S.S. (Suganti Shivaram), R.R., D.P., K.G., S.S. (Shubham Sood), N.K. and A.B. provided clinical perspectives and expertise for the study. A.S.S.C., V.K.M., B.B., S.S. (Shubham Sood), R.R. and D.P. conducted a literature review and drafted the manuscript. S.P.A. and A.S.S.C. conceived and crafted the illustrative figures. S.G., P.S., D.N.D., S.S. (Suganti Shivaram), S.D., D.M., S.R., D.R.L., A.B., K.K. and S.P.A. provided consulting and performed a critical review of the manuscript. A.S.S.C. and S.P.A. performed the cleaning and organization of the manuscript. S.P.A. provided conceptualization, supervision, and project administration. All authors have read and agreed to the published version of the manuscript.

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