Novel Method of Characterization of Dispersive Properties of Heterogeneous Head Tissue Using Microwave Sensing and Machine Learning Algorithms

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ABSTRACT A brain tumor is a critical medical condition and early detection is essential for a speedy recovery. Researchers have explored the use of electromagnetic waves in the microwave region for the early detection of brain tumor. However, clinical adoption is not yet realized because of the low resolution of microwave images. This paper provides an innovative approach to improve microwave brain tumor detection intelligently by differentiating normal and malignant tissues using machine learning algorithms. The dataset required for classification is obtained from the antenna measurements. To facilitate the measurement process, an Antipodal Vivaldi antenna with the diamond-shaped parasitic patch (37 mmx21 mm) is designed to operate with a resonance frequency of 3 GHz. The proposed antenna maintains a numerical reflection coefficient (S_{11}) value below -10dB over the entire UWB frequency range. In this paper, Waikato Environment for Knowledge Analysis (WEKA) classification tool with 10 cross-fold validation is used for comparison of various algorithms against the dataset obtained from the proposed antenna.

INDEX TERMS Brain tumor, Dielectric properties, scattering parameters, Classification, WEKA tool.

I. INTRODUCTION

The human body comprises numerous types of cells. These cells in the body grow and divide in an arranged manner to form new cells. These cells help to keep the human body healthy and ensure proper functioning. When some of these cells lose their ability to control growth, they grow without any order. The extra cells form a mass of tissue known as tumor. Thus, the tumor is formed by the combination of abnormal tissue present in the brain. A brain tumor is the accumulation of abnormal tissues inside the human head [1]. The most used diagnostic methods are Magnetic Resonance Imaging (MRI) Positron emission tomography (PET) and Computerized tomography (CT). But PET and CT use highly ionized radiations and MRI produces a strong magnetic field. Both approaches are expensive, time-consuming, and not portable [2]. So, an innovative approach is proposed in this paper based on dielectric property variation between normal and cancerous tissue. The dielectric properties such as permittivity and conductivity are high for cancerous tissue compared to normal tissue. These variations are useful to distinguish malignant tumor from healthy tissues in microwave imaging techniques.

Microwave imaging is a non-invasive imaging technique that is employed for microwave remote sensing, biomedical imaging, and non-destructive testing. Microwave imaging gains attention in recent days because of its non-ionizing radiation. It utilizes Electromagnetic waves to inspect an unknown target based on backscattered radar signals. There are three different types of microwave imaging namely active, passive, and hybrid microwave imaging. Passive microwave imaging refers to radiometric microwave measurements that measure the temperature difference between tumor and healthy tissues. An image is created based on the radiation emitted from the tissue. The drawback of this method includes low power radiation and ineffectiveness in handling cool substances close to the imaging domain. Active microwave imaging is a method of illuminating the region with a microwave source. Microwave energy is travelling through the target and scatter according to its electrical properties. It is mainly the preferred method for biological tissue sensing. Hybrid microwave imaging utilizes the combination of microwave and other imaging modalities such as acoustic or ultrasound techniques. Further, Active microwave imaging is classified into two categories such as quantitative (microwave tomography) and qualitative (radar-based microwave imaging). Quantitative microwave imaging is a method **by** which measurement of permittivity and conductivity from target enables image reconstruction. In the case of qualitative microwave imaging, the target is illuminated by UWB pulse, and a dielectric map is created to spot the location tumor from surrounding tissues based on reflection. The scattering map of this technique indicates the position and shape of a strong reflection. Here, the antenna is a key element for the detection of abnormality. The dispersion characteristics of head tissue are derived from a multilayer tissue phantom arrangement. This study focused on retrieving the dispersive properties of human head tissue to detect the abnormalities in the brain with the help of machine learning algorithms.

The essential requirements for microwave imaging techniques are high radiation, good spatial resolution, better depth of penetration, and portability. Early research in microwave imaging consists of hardware setup which includes a vector network analyzer and an antenna, which are driven by a software algorithm. The measurement of transmission power and reflected power are essential for the construction of the S-matrix. The matching medium is introduced to improve the coupling between an antenna and the head phantom. Researchers suggested employing Software Defined Radio (SDR) to overcome the complexity of vector network analyzer. There are numerous categories of antenna proposed for microwave head imaging such as Microstrip patch antenna, bowtie antenna, wideband textile antenna, EBG based antenna, H-slot antenna, triangular-shaped antenna, Vivaldi antenna, metamaterial-based antennas, 3D antennas, and open waveguides [3]. The above-mentioned antennas have the disadvantage of either narrowband (patch antennas) or complex design (metamaterial-based antennas and 3D antennas). The gain of the Vivaldi antenna is improved by a modified structure called Antipodal Vivaldi Antenna and the frequency response can be further improved by numerous techniques such as slot design, employing Metamaterial, phase dielectric lens and reflector, corrugated Vivaldi, the addition of parasitic and array design. In this article, a novel Ultra-wideband Antipodal antennas antenna is proposed with a parasitic patch [4][5]. Since it has a wide bandwidth, high radiation efficiency, and ease of fabrication. This study utilizes the bi-static antenna system in which one antenna act as a transmitter and the other antenna act as a receiver. Spherical head phantom is modelled in CST microwave studio 2020 software to mimic the real human tissues of the head [6][7][8]. The head phantom is illuminated by UWB microwave pulses and backscattered radar signals are recorded by the receiving antenna [9]. Image reconstruction becomes a challenging task in microwave imaging because of the inverse scattering problem. The inverse scattering problem has two major challenges such as ill- posed nature and nonlinearity. It is solved by either the quantitative method or the qualitative method [10]. Sometimes, FDTD simulation techniques are employed to check the measured value against simulated results. All these conventional methods of image reconstruction provide low resolution since the number of unknown quantities is larger than several equations [11]. So, Machine learning algorithms are applied to microwave imaging in various stages like segmentation, image classification, and clustering, etc. Here, Machine learning algorithm is applied to detect the presence of tumor in the brain using microwave measurement data directly without running complex image reconstruction algorithms [12][13][14]. The measurements are taken at multiple positions along with the head phantom. A new technique of post-processing these simulated results will be shown with the help of a machine learning algorithm [15][16]. The dataset is created from the antenna measurements which include the following attributes such as class, frequency, reflection coefficients (magnitude and phase in separate columns), and electric field values [17][18]. Then, the dataset is pre-processed to create an arff file format from a csv file. WEKA tool is one of the most familiar open software tools for data mining. Data mining is a field of research for extracting a hidden pattern from a large amount of data. Data mining techniques and machine learning algorithms are helpful in the early detection of diseases like cancer. Data cleaning, data integration, data selection, data transformation, data mining, pattern evaluation, and knowledge presentation are the steps involved in data mining. There are three techniques commonly found in data mining are an association, classification, and clustering. Association is mainly intended to find the relation between co-occurrence of item in a crowd of data. Classification is a supervised learning method to classify the data. Clustering is an unsupervised technique of grouping similar data. WEKA works based on the command-line interface. The main objective of this paper is to apply a classification technique to predict the presence of a tumor in the head tissue from the measured data. This involves classifying the dataset and then determining the performance of various algorithms in the process of diagnosis. J-48, Naive Bayes, random forest, SVM, and K-NN are some of the classifiers used in data mining.

Dielectric properties are learned from 1001 samples using head phantom created in CST software. Machine learning takes appropriate decisions based on the available dataset and creates a mathematical model for future lesion detection [19].

The main contribution of this paper includes the following steps

1. To create a dataset by the data acquisition set up (Design of an Antenna and Head phantom)
2. Data pre-processing
3. Splitting of training data set and testing data set

4. Classifying the dataset with different Machine learning algorithms
5. Performance analysis to identify the best algorithm in diagnosing the disease.

The paper is organized as follows. Section 2 explains the methodology and creation of the dataset, in Section 3 concentrates on the machine learning algorithms to be followed for detection, Section 4 explains about results and discussion.

II. METHODOLOGY

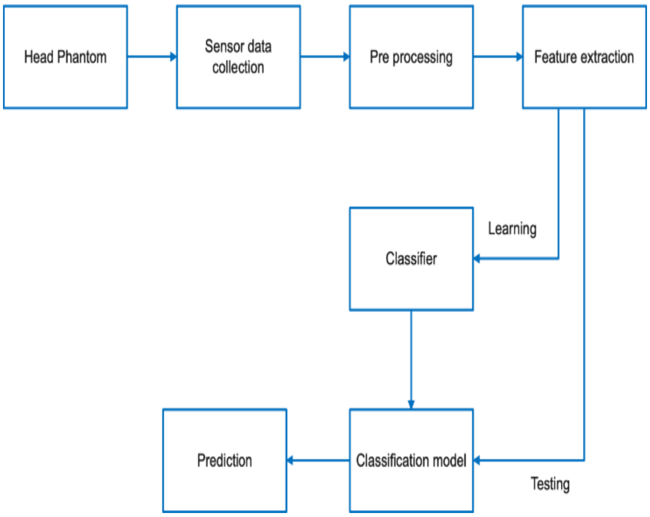

FIGURE 1. Processing steps in detection of Brain tumor

The electrical properties of multilayer head tissue and its interaction with EM field are analyzed by scattering properties. Several layers of head tissue are used for analyzing complex reflection and transmission characteristics. Next, the system employs one or more sensors (antennas) surrounding the object of interest. Microwave reflected signals can potentially be employed to identify tumors in the head phantom with the help of Machine learning algorithms [20][21][22] as shown in figure 1. WEKA tool helps to make prediction about the presence of brain tumor in an efficient way. First, the data collected from the sensors are processed and applied to WEKA tool for prediction with different Machine learning algorithms.

A. DESIGN OF DATA ACQUISITION SYSTEM

Antennas are the key elements in success of microwave imaging system. Generally, the microwave imaging system is implemented by wideband, reliable, and cost-effective antenna structure. Antipodal Vivaldi antenna with FR4 dielectric substrate is proposed for sensing dielectric permittivity variation. The final configuration is designed in CST Simulation software 2020. The conventional Antipodal Vivaldi antenna has the disadvantage of narrow bandwidth because of undesired radiation travelling along the flare termination section. The addition of a parasitic patch in the flare aperture of an Antipodal Vivaldi antenna effectively focuses the energy on the end fire direction. It utilizes the field coupling between the main radiating patch and inserted triangular parasitic patch to improve the directivity. The dimensions of the triangular parasitic patch are optimized so that the off-axis radiation is limited. There is a strong field coupling to asymmetric parasitic patch and produces enhanced radiation. A diamond shaped parasitic patch is introduced in the midpoint of two flares. This couples the main radiating beam to focus the radiation on the end-fire direction and improves the field coupling effect. The design utilizes the dielectric substrate of FR4 (4.3) and thickness (Ts=1.6 mm) and the lower operating frequency f_L is calculated by equation (1).

$$f_L = \frac{c}{(2w\sqrt{\varepsilon_{eff}}\,)} \qquad (1)$$

Where w denotes the antenna width
c =3x10^8 (free space light velocity)
ε_{eff} = the effective dielectric constant

$$\varepsilon_{eff} = \frac{(\varepsilon_r+1)}{2} + \frac{(\varepsilon_r-1)}{2}\left[1+\frac{12T_s}{w}\right]^{\frac{1}{2}} \qquad (2)$$

ε_r =Relative permittivity of the substrate material
The design equations of Antipodal Vivaldi antenna are shown in equation (3) and (4).

$$Y = \pm(C_1 e^{ax} + C_2) \qquad (3)$$

Where C1 and C2 are given as

$$C_1 = \frac{y_2 - y_1}{e^{ax_2} - e^{ax_1}} \text{ and } C_2 = \frac{e^{ax_2} y_2 - e^{ax_1} y_1}{e^{ax_2} - e^{ax_1}} \qquad (4)$$

Where x1, y1 and x2, y2 are constants for selecting the endpoints. The unknown 'a' is the increment value of flare. The conventional structure is represented in figure 2. and the proposed layout is shown in figure 3. The dimensions are adopted as described in table 1.

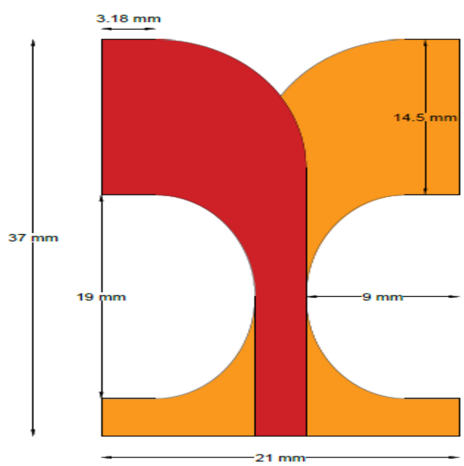

FIGURE 2. Basic Antipodal Vivaldi Antenna

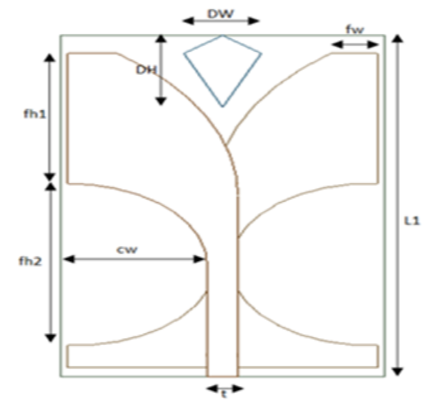

FIGURE 3. Antipodal Vivaldi antenna with parasitic patch

TABLE I. Antenna Dimension

Parameter	Value (in mm)
DW	5
DH	8
fw	3.18
fh1	14.5
fh2	19
cw	9
L1	37
T	1.6

B. ELECTRICAL PROPERTIES OF DIFFERENT HEAD TISSUES FOR EM SIMULATION ENVIRONMENT

Head phantom is constructed in CST Microwave simulation studio software to emulate the electrical properties of real head tissue. Spherical, hemispherical and MRI derived phantoms are the types of models reported in recent literatures. The tumor cells have high water content compared to normal tissues. The electrical properties such as conductivity and permittivity are 10% higher than healthy tissue. Figure 4. represents the bi-static radar model-based approach for detection tumor inside head phantom. Spherical brain phantom and target tumor structure are created along with bi-static antenna structure. The interaction between EM waves and head tissue is analyzed by modeling head phantom to emulate real human head at 3 GHz. The dielectric properties of various head tissues with seven layers are indicated in table II. The microwave signals penetrate through the multilayer head tissue and reflections are collected at multiple positions. The presence of tumor is identified by high reflection due to electrical property difference between normal and tumor tissue. Here, the tumor is modeled as sphere with radius of 5 mm.

TABLE II. Heterogeneous Human Head Phantom Model and Its Properties at 3 GHz

Name of the Tissue	Thickness (mm)	Radius (mm)	Permittivity	Conductivity (S/m)	Loss tangent (tan δ)
Brain	3	81	43.22	1.29	0.78
CSF	1	84	70.1	2.3	0.385
Dura	4	85	46	0.9	0.292
Bone	7	89	11.4	0.03	0.252
Fat	2	96	5.54	0.04	0.145
Skin	4	98	45	0.73	0.32
Tumor	5	5	55	7	1.05

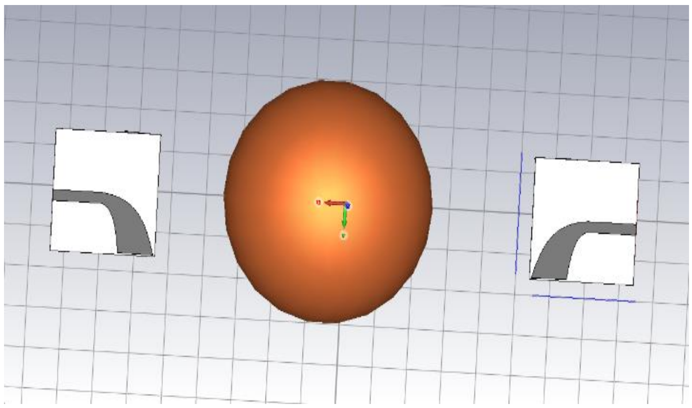

FIGURE 4. Virtual phantom in CST microwave studio software

The proposed antenna is rotated around head phantom axially to create a synthetic array structure and measurements are taken at each position. A short UWB pulse is emitted from the antenna. The antenna is kept at 5 mm from the human head. It transmits a UWB microwave pulse into the head phantom, and the backscattered signals are collected at multiple positions from the antenna. The transmission coefficient (S_{21}) and reflection coefficient (S_{11}) are measured over the frequency range. The simulation results are obtained in the form of text file with two columns and 1001 rows. The measurements are made with tumor and without tumor. This is used for creating dataset with antenna measurement parameters.

C. DATASET PRE-PROCESSING

3D Electromagnetic Simulation is done by Computer Simulation Studio (CST) 2020 version. An Ultra-wide band antenna at a resonance frequency of 3GHz is simulated and planar scanning is employed to measure S parameters at different positions of brain phantom. The simulation output is recorded as a raw data file and preprocessing is done to remove unwanted signals. The simulation results are represented in table III.

TABLE III. Frequency Domain Values of Simulation Result

Frequency (Hz)	S_{11}(dB) Without tumor	S_{11}(dB) With tumor
3035000000	-21.451100	-19.451100
3125000000	-14.707300	-13.707300
3170000000	-16.988860	-16.988860
3260000000	-13.818840	-13.818840
3350000000	-13.052093	-13.052093
3395000000	-15.015243	-15.015243
3440000000	-15.711979	-15.711979
3485000000	-14.295147	-14.295147
3575000000	-13.204520	-13.204520
3620000000	-14.451100	-14.451100
3665000000	-19.697750	-17.697750
3755000000	-19.988860	-19.988860
3845000000	-25.998760	-23.998760
3935000000	-23.532290	-21.532290
4025000000	-33.005910	-28.005910
4070000000	-20.795890	-22.795890
4160000000	-21.719980	-21.719980
4205000000	-23.540320	-23.540320
4250000000	-15.981890	-15.981890
4340000000	-16.080500	-16.080500
4385000000	-16.537120	-15.537120

The machine learning method utilizes learned parameters to detect the presence of brain tumor without creating images. The dataset from the antenna measurements is converted to arff format before applying to WEKA tool. This study is done with 10-foldcross validation in which dataset is split into 10 equal folds to produce accurate results.

III. MACHINE LEARNING ALGORITHMS

A. BAGGING ALGORITHM

Bagging or bootstrapping aggregating is a method of enhancing the accuracy of classification process. This is mainly applicable for classification of remote sensing data and prediction of several kinds of medical data. This algorithm helps to prevent over fitting. Bagging algorithm reduces variance thereby increase the accuracy.

B. IBK ALGORITHM (INSTANT BASED LEARNER)

KNN algorithm is also known as IBk algorithm with parameter k. It is a non-parametric algorithm based on supervised learning. It is used for classification and regression. It works on the similarity between a new data and training data. The classification problem is solved by calculating the distance metric between observations like Euclidean Distance. In K-nearest neighbor algorithm, the parameter K represents the number of closest neighbors.

C. RANDOM FOREST ALGORITHM

Random Forest algorithm is a collection of classifiers which combines the output of multiple decision trees to obtain single output. It is based on supervised learning technique.

D. J48 ALGORITHM

Java implementation of Quinlan's C4.5 algorithm in the WEKA tool is called J48 algorithm. This open-source algorithm is proposed to create a trimmed C4.5 binary tree. J48 develops a decision tree utilizing the training data. J48 decision tree can deal with characteristics, lost or missing attribute estimations of the data and varying attribute costs. For categorization problems, it is one of the most useful decision tree algorithms. To mimic the classification process, it combines a top-down and greedy search across all available branches to generate a decision tree. It must first form a decision tree based on the attribute values of the available training data to categories a new item.

E. SUPPORT VECTOR MACHINE (SVM)

SVM is a supervised learning classification technique that examines data for classification and regression. It is regarded as one of the most capable machine learning algorithms for categorizing problems.

F. NAIVE BAYES ALGORITHM

NB is a machine learning algorithm that is applied to attributes with strong naive presumptions. One of the most basic Bayesian models is the NB. NB calculates the target variable's probability.

G. CLASSIFICATION AND REGRESSION TREE (CART)

CART is a machine learning decision tree algorithm that aids in the prediction of a target variable while considering other variables. In a tree format, Decision Tree generates classification or regression models. Because the problem is handled in the form of a tree, decision trees are simple to comprehend.

IV. RESULTS AND DISCUSSION

A. PARAMETRIC ANALYSIS OF ANTENNA MODEL

The proposed antenna results are evaluated by CST Microwave Studio simulation software 2020.The important parameters which are required for creation dataset like Voltage Standing Wave Ratio (VSWR), Radiation pattern, Electric field values with head tissue and without head tissue are measured. The value of reflection coefficient with and without tumor is shown in figure 5. The radiation pattern provides good directivity over the frequency band of operation. The far-field patterns are measured at 3.2 GHz and 4.5 GHz. The directivity of designed antenna reaches maximum value of 6.7 dBi at resonance frequency as represented in figure 6. The fabricated antenna structure is illustrated in figure 7.

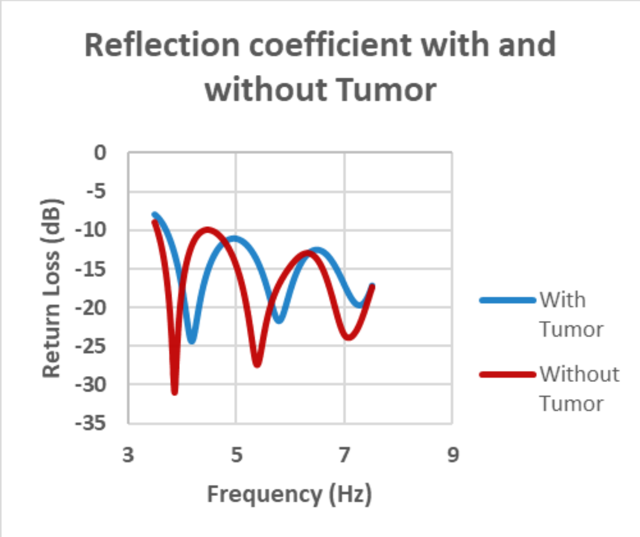

FIGURE 5. Variation of Reflection coefficient with frequency

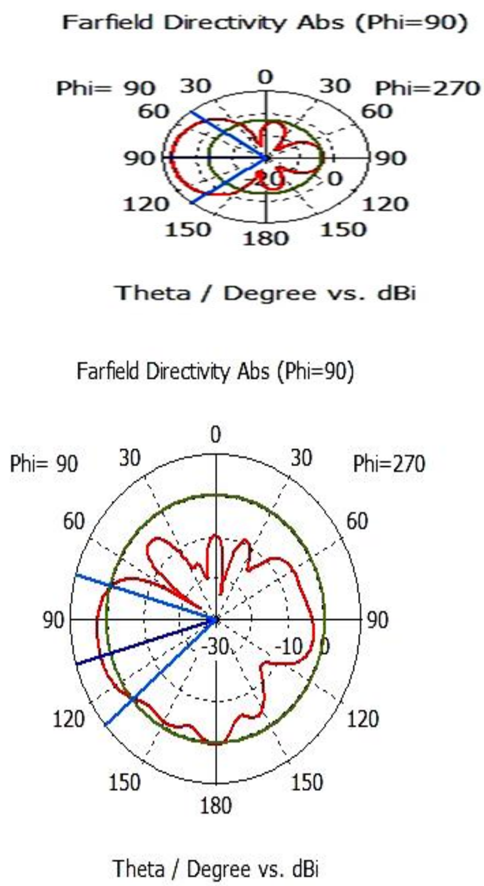

FIGURE 6. Radiation pattern of Antenna with frequency at frequency (a) 3.2 GHz (b) 4.5 GHz

FIGURE 7. Fabricated Antenna

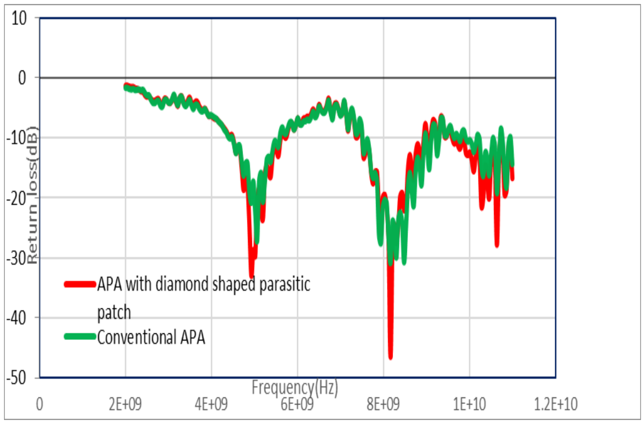

FIGURE 8. Reflection coefficient of fabricated structure

The measurement value indicates that parasitic patch in the aperture of Antipodal antenna improves reflection characteristics compared to conventional structure. The fabricated antenna structure is represented in figure 7. The measured results are shown in figure 8. The measurement S_{11} is used to differentiate normal tissue from tumor tissue. This can be used as a preliminary diagnostic tool for medical imaging systems. Finally, WEKA tool classifies the dataset and predicts the presence of tumor. The improved performance is obtained when numbers of data acquisition points are increased. Table IV illustrates the results of different data mining algorithms.

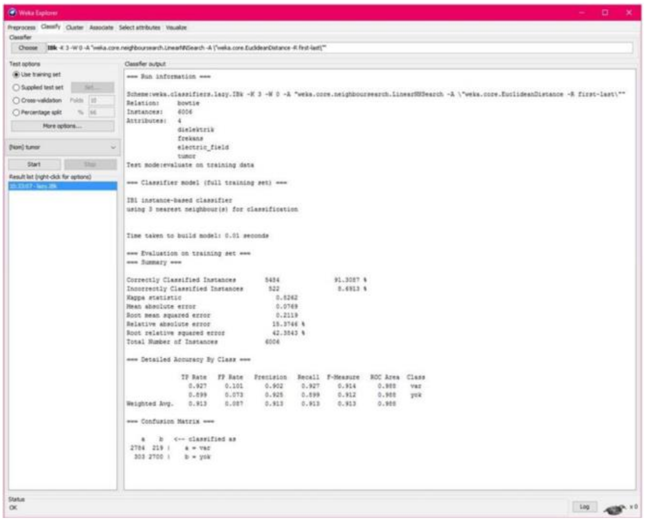

FIGURE 9. The result of IBK algorithm on WEKA tool

The accuracy rate is calculated by total number of correct predictions divided by the total number of classifications and indicated in equation 5. The dataset is divided into k equal parts (K- fold cross validation). One-fold is used for testing and the rest k-1folds for training. This is repeated for k times and the average value is taken for prediction. The result of KNN algorithm is illustrated by WEKA tool output as shown in figure 9.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (5)$$

Where,
TP = True Positive
TN = True Negative
FP = False Positive
FN = False Negative
Table V illustrates the performance comparison of different Microwave Imaging System reported in literature. Even though ref [12] and ref [17] exhibits maximum accuracy compared to the proposed system, it has major disadvantages of complex antenna array and narrow bandwidth. The design of antenna array without mutual coupling effect is difficult to realize in practice. Our proposed method uses bistatic method and measurements are taken at various positions by rotating them around the head phantom.

TABLE IV. Results of different Data mining algorithms

Algorithm	Accuracy Rate for various Fold Number										Average Accuracy
	1	2	3	4	5	6	7	8	9	10	
Random Forest	90.2	92.7	90.8	91.4	93.2	91.6	93.2	94.4	91.8	90.8	92.01
Bagging	90.3	91.7	89.4	91.3	91.8	88.9	92.0	93.0	90.7	89.5	90.9
Simple CART	89.4	92.0	89.0	89.9	90.5	88.4	91.7	91.0	89.8	89.3	90.1
IBk	93.3	92.0	89.7	89.5	89.5	91.3	93.0	93.7	90.0	89.8	91.36
Classification Via Regression	88.5	88.9	86.0	88.2	89.7	88.7	92.3	89.7	88.0	89.2	88.9
Decision Tree	86.4	89.0	86.5	87.7	90.2	88.2	87.0	90.3	88.5	87.8	88.2
BFTree	88.9	87.7	88.5	86.4	86.5	88.7	89.7	90.2	86.3	88.5	88.1
Bayes Net	61.9	60.1	59.9	55.4	60.2	58.4	60.2	61.5	59.3	58.2	59.5
Decision Table	61.9	60.1	59.9	55.4	60.2	58.4	60.2	61.2	59.3	58.2	59.5

TABLE V. Performance comparison of different Microwave Imaging System reported in literature

Reference	Antenna structure	Dimension (in mm)	Frequency range (GHz)	Data mining tool and Algorithm used	Application	Accuracy
[12]	Not mentioned	Not mentioned	1-6 GHZ	K-Nearest Neighbours Algorithm	Breast cancer	96.2%
[13]	Bow-tie antenna	110x178.75	3.1-10.6 GHz	Weka tool and K-Nearest Neighbours Algorithm	Breast cancer	90%
[17]	complex Nine antenna arrays	53 × 22 × 21.575	1-4 GHZ	YOLOv3 deep neural network	Brain Tumor	94.62%
[20]	Microstrip Patch	31.68 ×	3.1-10.6	MATLAB and delay	Brain	Image is

	antenna with EBG structure	31.02	GHz	and sum algorithm	Tumor	reconstructed and classification is not done.
[21]	Implantable antenna	10×0.5	2.4 GHz	Specific Absorption Rate analysis	brain monitoring	Classification is not done.
This study	Antipodal Vivaldi antenna with parasitic patch (Bistatic arrangement)	37×21	3.1-10.6 GHz	Random Forest, Bagging, Simple CART, Decision Tree etc. are implemented in Weka tool.	Brain Tumor	94.4% (Random Forest)

V. CONCLUSION

In this paper, an Antipodal Vivaldi Antenna with parasitic patch is designed for detection of brain tumor. The designed antenna provides wideband, high efficiency and directional radiation characteristics. A seven-layer head phantom is developed to study about the interaction of electromagnetic waves with head tissues. The electric field values with and without tumor are measured. Finally, the machine learning algorithm is applied to the dataset for early detection of brain tumor. The WEKA tool provides a maximum accuracy of 94.4% using Random Forest algorithm. The future work includes developing a hardware phantom to emulate tissue properties.

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