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Electromagnetic Imaging: A Novel Approach for Brain Stroke Detection and Diagnosis

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ABSTRACT

Electromagnetic Imaging (EMI) has emerged as a promising non-invasive technology for brain imaging, leveraging dielectric property variations in healthy and stroke-affected tissues. This review explores EMI's principles, hardware architecture, and computational methodologies employed for stroke detection and classification. The paper examines EMI's advantages, challenges, and future clinical implications, emphasizing its potential to revolutionize neurodiagnostic methods.

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1.Introduction

The electromagnetic properties of biological tissues vary with physiological and pathological conditions, making EMI a viable tool for stroke detection. EMI differentiates hemorrhagic from ischemic strokes based on dielectric property variations. Each type of biological tissue possesses distinct dielectric properties that fluctuate with frequency. Any alterations in the physiological or pathological state of a tissue lead to corresponding changes in its dielectric characteristics, thereby influencing its response to electromagnetic (EM) waves. For instance, a hemorrhagic stroke, characterized by brain bleeding, increases tissue permittivity and conductivity, whereas an ischemic stroke, caused by a blood clot obstructing circulation, results in lower dielectric properties compared to healthy tissue. Consequently, specialized sensors can be designed to emit specific signals, detect scattered responses, and extract crucial information for imaging and monitoring these changes.

Electromagnetic imaging (EMI) has been extensively studied for developing diagnostic tools that are non-invasive, portable, cost-effective, and free from ionizing radiation. In brain imaging, EMI has significant potential as an on-site, real-time, or near real-time method for stroke detection and classification. An EMI system consists of two primary components: the hardware, which includes an array of EM transceivers to illuminate the brain and collect scattered waves, and the software, which utilizes specialized algorithms to process the data and generate an image of the brain, highlighting stroke-affected regions. The fundamental principle of EMI relies on the contrast in dielectric properties between normal and stroke-affected tissues.

Although EMI techniques have been successfully demonstrated in laboratory experiments, several challenges hinder their clinical adoption. These include hardware limitations, such as the number, type, and placement of sensors (antennas), the efficiency of coupling and decoupling media, and interference from external noise and clutter, which can sometimes be more pronounced than stroke-induced signals. Additional difficulties arise in selecting the appropriate frequency band, ensuring accurate system calibration, refining pre- and post-processing software algorithms, and managing computational demands. One of the most significant hurdles is detecting extremely weak stroke signals, often below -50 dBm for deeply located abnormalities, amid stronger signals from surrounding tissues and structures.

To facilitate the application of EMI in non-invasive tissue assessment and monitoring, various techniques have been developed. These methods are broadly classified into radar-based and tomographic imaging approaches, although artificial intelligence and statistical methods are also gaining traction. Radar-based techniques utilize a wide frequency spectrum to enhance image resolution and employ back-projection methods to identify anomalies such as strokes within the scanned area.

Electromagnetic tomography (EMT), another widely used technique, maps the dielectric properties of brain tissue by processing scattered EM fields with computationally intensive iterative algorithms. However, due to constraints such as limited space around the head, the relatively large size of EM sensors, and the numerous unknown variables in brain mapping, EMT is inherently an ill-posed problem. To address this, optimization techniques are applied, though they are nonlinear and require substantial computational resources and time to resolve.

The clinical electromagnetic brain scanner represents a breakthrough in diagnostic imaging, utilizing electromagnetic principles to analyze brain function and structure. This innovative technology bridges the gap between conventional imaging methods and advanced neurodiagnostic techniques, providing a non-invasive, high-resolution approach to studying brain activity. This review explores the core principles, clinical applications, advantages, and future directions of electromagnetic brain scanning.

This review discusses the working principles of EMI, its hardware and software components, and its effectiveness in real-time stroke diagnosis.

2. Principles of Electromagnetic Brain Imaging

In the first step, the system is calibrated using well-defined phantoms. The system is then used to scan the patient's head and capture scattered signals, which are calibrated against calibration phantom signals. The calibrated data is then processed using a neural network to estimate the contour of the head slice being scanned. Those boundaries are then fed to line crossing, direct mapping, and beamography, which work in an iterative collaborative manner to detect, localize and classify any stroke. In parallel, a tripartite data-driven algorithm is used to map the dielectric properties of all brain tissues. Finally, all the generated images from those algorithms are fed to a fusion algorithm, to give the final image, which shows the location, size, and shape of the stroke in addition to the internal tissue distribution.

2.1 Dielectric Property Variation in Brain Tissues

- Hemorrhagic strokes increase dielectric properties due to bleeding.
- Ischemic strokes reduce dielectric properties due to clot formation.

3 EMI System Framework

- Calibration using phantom models
- Data acquisition through antenna arrays
- Image formation via neural networks and computational algorithms

a) Device Framework

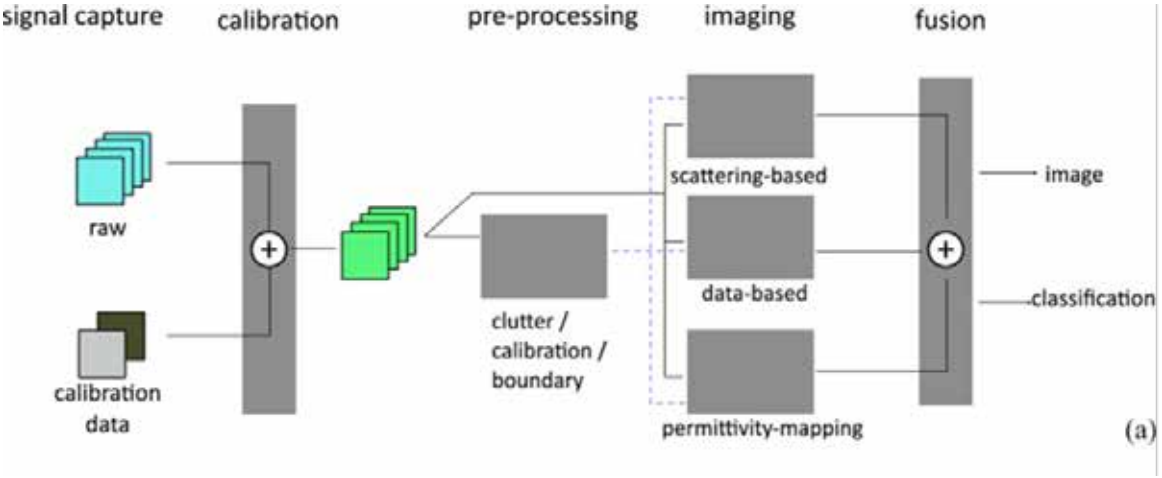


Fig 1(a): Shows the framework of the device

(b) Main elements of the device:

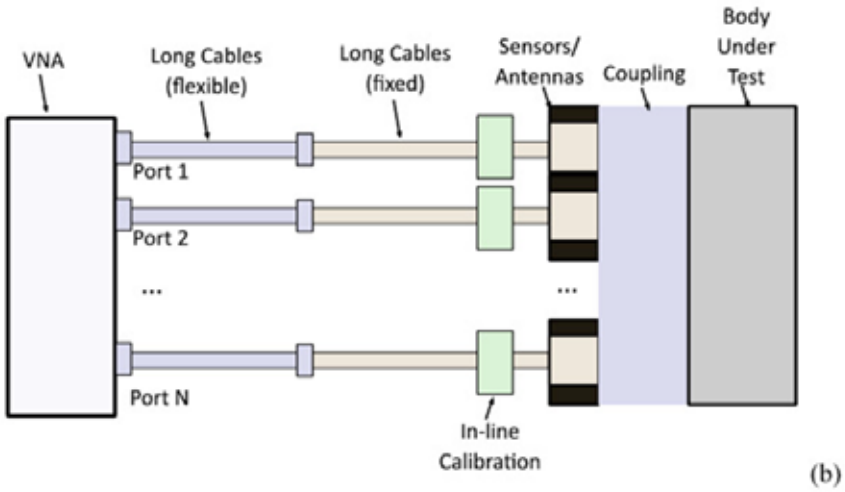


Fig 1(b): Shows the main elements of the device

A coupling medium between the antenna array and the head, an antenna array surrounding the head and operating at the low microwave frequency band, an in-line calibration unit for each antenna element, two sets of fixed and flexible cables connecting the antenna array to the multi-port vector network analyzer.

(c) The developed device that meets the clinical requirements.

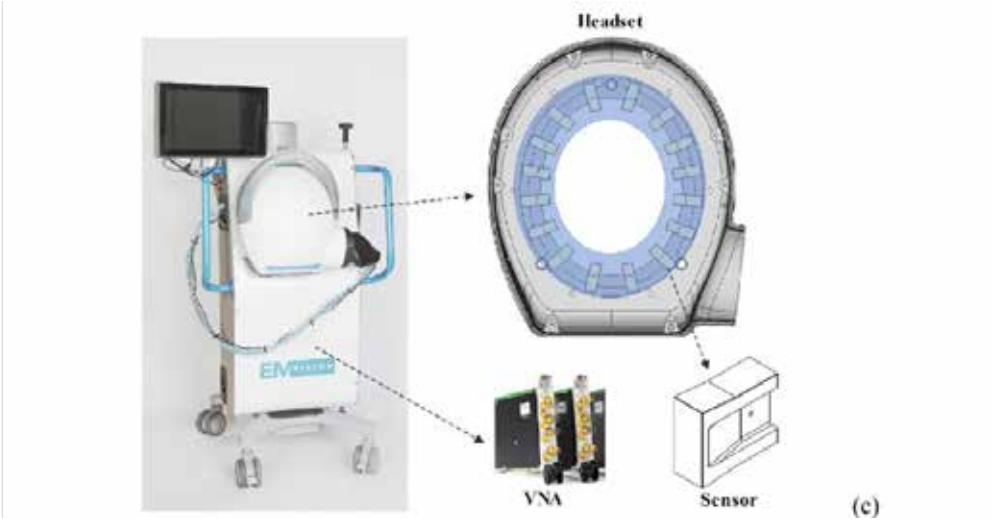


Fig 1(c). Show the device and its components that meets the clinical requirement

The frequency range for the reported device is selected to balance the requirements of theoretical resolution and penetration of EM waves into the head. Higher frequencies would provide higher resolution but would have limited penetration into the head. Most of the signal would be reflected and absorbed by the skin and skull layers of the head. Lower frequencies have higher penetration but also require larger antenna structures and provide lower resolution. The size of the antenna also dictates the number of antenna elements that can fit around the head. The richness of the information provided to an EMI device is improved with more frequency bandwidth, more antenna elements, and antennas that allow signals to penetrate over the entire head. Based on these needs, the reported device operates in the frequency range of 0.7–1.8 GHz and has 16 antenna elements.

A Keysight PXI Vector Network Analyser (VNA) is used as a 16-port transceiver for data acquisition. The VNA excites the transmitting antennas serially and captures signals received by all antennas at each excitation. The dynamic range of the system is selected to ensure that the system can capture both the strong signal reflected off the boundary of the head as well as the much weaker signal reflected off anomalies inside the head. As the ratio of these two values does not change with increasing transmitted power, that power is maximized while ensuring the subject's safety as per relevant guidelines[40] and keeping the system-level noise to a minimum. This ensures that the lowest level signal with information from inside the head is above the thermal noise level. Each of the main elements is discussed in the following paragraphs.

Coupling medium

It is a mixture of materials selected to ensure antenna-head matching and thus maximum EM penetration into the head. The medium has a dielectric constant of 45 and a conductivity of 0.15 S/m at 1 GHz. It is contained within a 1 mm thick silicone membrane and fills the void between the antennas and the head. It is designed to have a minimal loss to ensure that the signal is not attenuated significantly before entering the head. A fluidic system is utilized to maintain a consistent pressure of the coupling media inside the membrane throughout imaging, consisting of a peristaltic pump, pressure sensor, and pressure relief valve. This was also used to retract the membrane to allow the patient to be properly positioned within the system before inflation. To fill the region between the head and antennas' apertures with coupling liquid, a thin silicone membrane is attached above and below those antennas at the edges of the decoupling region to allow the entire area within the main beam of the waveguide antennas to be filled with the coupling liquid while keeping the liquid separate from the head. Using this membrane ensures that the patient does not endure discomfort from being in contact with the liquid, which should not be contaminated by the patient or environment, allowing it to be reused for the shelf life of the coupling medium. The used membrane has a thickness of 0.5 mm, and thus has negligible impact on signal penetration, appearing similar to the patient's hair.

A peristaltic pump, housed within the trolley, is used to transport the liquid coupling medium from the reservoir (also housed within the trolley) to the membrane. Thin PVC tubing, which is connected to the headset inlet and outlet, is used to link the membrane and the reservoir. These tubes are also enclosed in the harness containing flexible RF cables. A digital pressure gauge monitors the pressure being applied to the head and provides feedback to the pump so that the desired pressure is maintained. Using this system, reliable data is enabled by conforming the membrane to the patient's head shape as much as possible. The

maximum pressure is 0.5 PSI when measuring to ensure the patient's comfort, and so fail-safes are built into the system so that this is not exceeded while on a patient.

Decoupling medium

To further improve the signal information from the head, a lossy medium surrounding the antennas prevents any stray signals from directly traveling between antennas, or further distorting useful signals via multiple reflections. This decoupling layer is designed using a polymer composition with a permittivity close to 45, and a significant loss (conductivity of 4.5 S/m at 1 GHz) to ensure that signals entering this medium can be ignored.

Absorber

External EM interference, generated by other wireless devices, such as mobile phones, operating at the same frequency band, is a major problem for EMI. Thus, in addition to the decoupling medium, EM shielding techniques or absorbers are used to mitigate any interference. A metal-backed EM absorber is utilized in the reported device to provide shielding from outside signals and absorb any internal stray signals. The absorber consists of a multilayer of magnetic substrates and a single-layer lossy frequency selective surface. A single-square loop geometry is used for the lossy surface, which is fabricated using the resistive sheet. The magnetic layers are made by mixing different ratios of carbonyl-iron powder with a silicone elastomer called polydimethylsiloxane. The absorber provides −15 dB reflectivity over the entire used bandwidth.

EM sensor antennas

Due to the complexity of the human head, the device uses a combination of different algorithms, which require the antenna to (a) operate in a wide range of frequencies and pulse durations, (b) have a constant phase center across the operating frequencies, (c) be compact such that more antenna elements can be placed around the head to obtain more information, and (d) provide directional radiation patterns to concentrate the transmitted waves towards the head. All the above requirements make the antenna design challenging. It is based on a waveguide-type radiator. It has a rectangular aperture, while the rest of the antenna surface is covered by conductive paint. To reduce the operating frequency to start from 0.65 GHz as needed for head imaging while keeping the antenna compact, it is filled with loss-less high-permittivity ceramic to ensure a high radiation efficiency. The wideband operation is achieved by modifying the shape of the waveguide. The feeding section, i.e., the part of the waveguide near the feeding position, works as a double-ridge waveguide to reduce the operating frequency for antenna miniaturization purposes. A tapered transition from the ridge waveguide to the rectangular aperture is used to improve impedance matching. Also, by lengthening the height, the antenna provides a more focused beam in the Z direction, which helps avoid clutter from above and below the array

4. Computational Algorithms in EMI

Algorithm-I: Boundary detection- Incorporating boundaries of the imaging object as a priori information to imaging algorithms can significantly improve the performance of EMI systems. To avoid overly complicating the device by using additional sensors, a multi-layer deep neural network method is used to estimate the boundary (external contour) of the imaged object using the calibrated EM data. Reflection coefficients are useful parameters for boundary detection algorithms based on machine learning. The model enables fast scan and image creation while eliminating the need for additional devices in accurate boundary estimation.

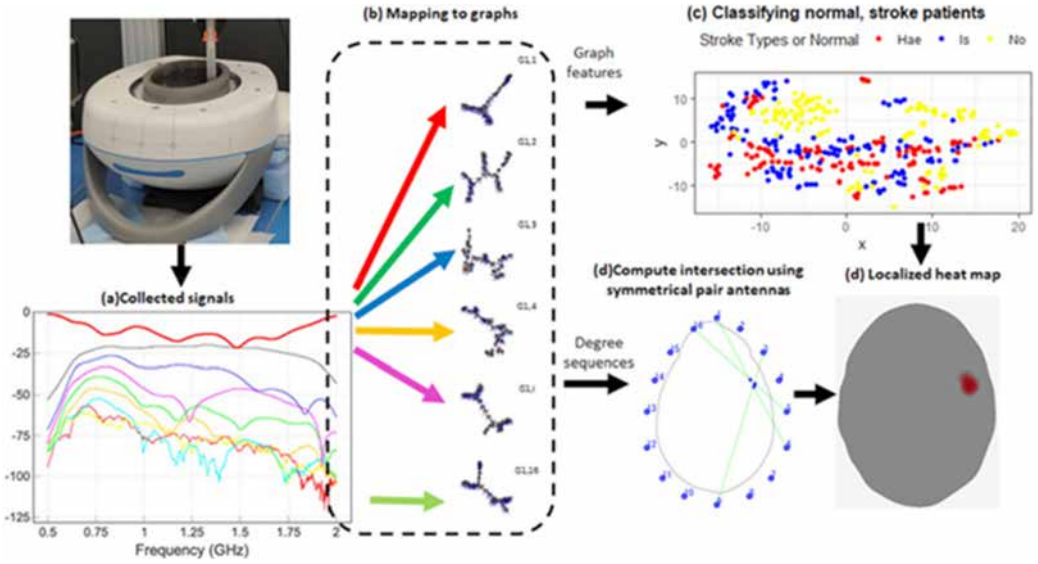


Fig.2: Shows mixed graph similarity and line crossing are used to detect, localize, and classify strokes

Algorithm-II: Mixed graph similarity and line crossing are used to detect, localize, and classify strokes. Both algorithms first convert the calibrated time-domain data into a horizontal visibility graph based on a linear fast-weighted horizontal visibility graph algorithm.

Algorithm III: Receive calibrated data as a matrix (in a 16×16 Cartesian grid) to generate a polar grid with a unique parameter mapping scheme as shown by individually color-coded cells.

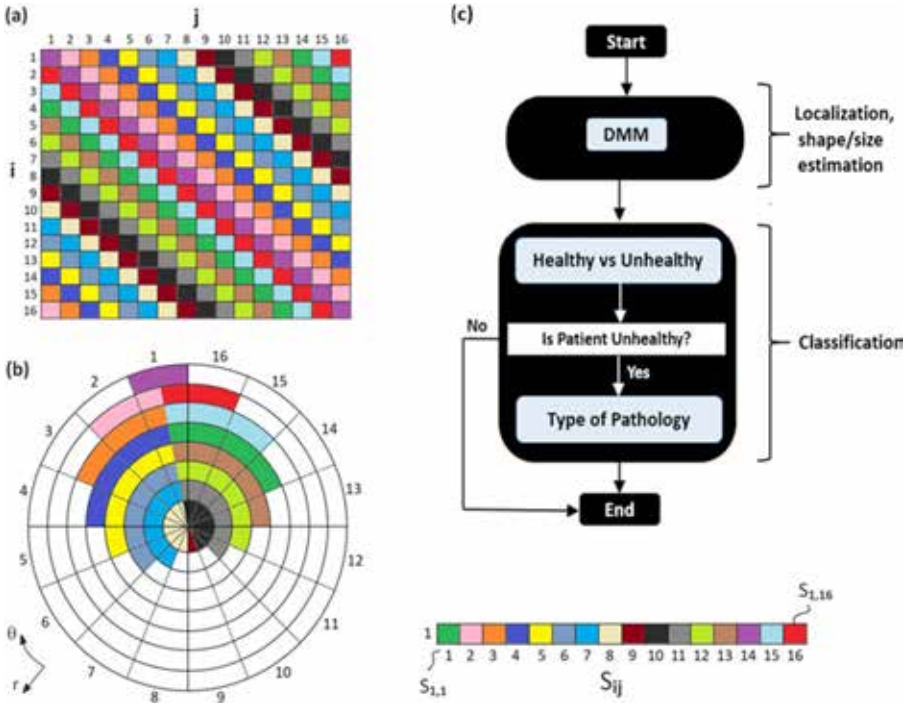


Fig.3: Shows steps involved in acquisition of data for the image formation

The included subplot shows one example of the encoding scheme for antenna no.1, and this scheme is repeated for all other antennas in succession. Another subplot shows the DMM flowchart wherein localization is performed first, followed by classification of the patient in terms of '*healthy vs unhealthy'* and *'ischaemic vs hemorrhagic'* stroke type if *'unhealthy'* is detected. Classification solvers also employ the DMM core algorithm as part of their kernel, along with statistical calculations to estimate the likelihood levels of classified types.

Algorithm-IV: Beamography, i.e. beamforming plus tomography, detects and localizes strokes within the brain by performing two major tasks 1) clutter mitigation, and 2) target focusing. Clutter mitigation is accomplished through symmetry and average subtractions to suppress the clutter returns from other tissues than the stroke.

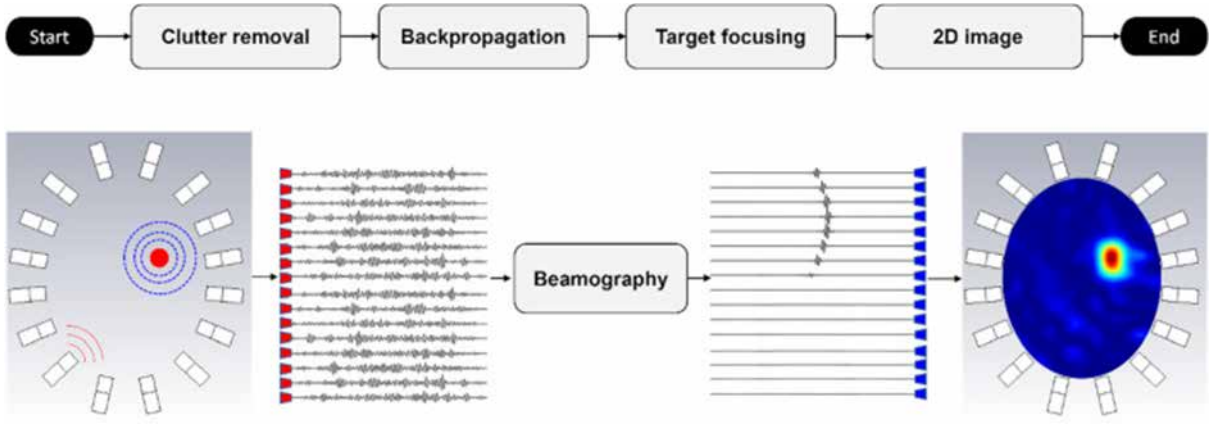


Fig. 4: Shows the steps involved in the beamforming plus tomography

Beamography detects and localizes strokes by performing two tasks (1) clutter mitigation, and (2) target focusing. Clutter mitigation is accomplished through symmetry and average subtractions. Marginal distortions due to the inevitable anatomical brain asymmetry and the head displacement are alleviated by average subtraction, where the average of all signals at all frequency samples is subtracted from each of them. After clutter removal, the data captured by each sensor is back-propagated to the imaging domain, using the domain Green's function to calculate the field observed at each point in the brain for each transmitter–receiver pair and each frequency sample. Those calculated fields are then superposed to construct the final image. The location of the stroke in this method is shown by a higher intensity compared to healthy tissues.

Algorithm-V (Fig. 6): Unsupervised ML algorithm (Expected Value-based Stroke Localization (EVSLA)) is based on a statistical comparison of symmetrical brain patches and takes advantage of a highly symmetrical human brain

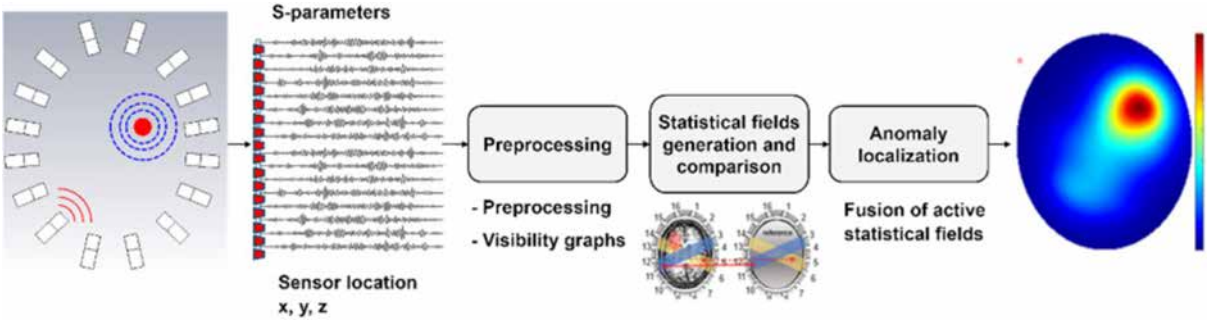


Fig.5: Flowchart of stroke localization with EVSLA algorithm.

The algorithm takes S parameters of the raw measurement and calibration data in the frequency domain and locations of sensors as inputs. In the preprocessing step, the algorithm performs inverse Fourier transform (IFFT) of collected S parameters and generates visibility graphs. Generated graphs are used to construct statistical fields and compute the similarity levels between the calibration and raw data. Regions with higher dissimilarity are kept active and used for fusion. The obtained fusion matrix represents the likelihood of each pixel being affected by a stroke. Visualization of the fusion matrix shows the stroke location.

Algorithm-VI: EMI medical imaging in the microwave regime is a hard problem notorious for instability and under-determinism. This two-pronged problem is tackled using dielectric mapping via DeepHead algorithm as a new imaging paradigm. It is a two-pronged solution that uses double compression to maximally utilize the cheap unlabelled data to a) provide a priori information required to ease under-determinism and b) reduce the sensitivity of inference to the input.

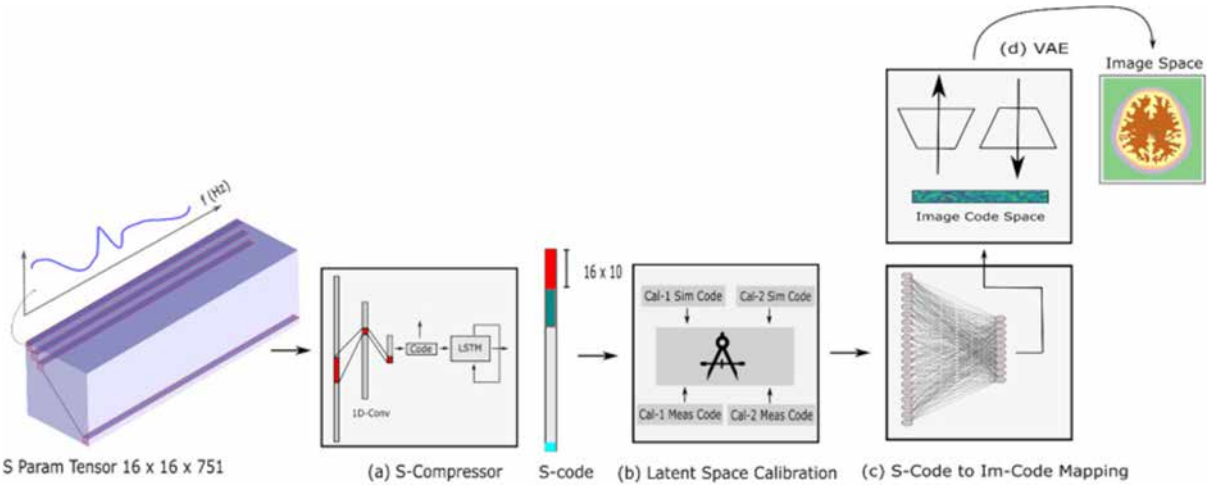


Fig. 6: Deep Head for dielectric mapping of the brain.

It uses double compression to maximally utilize the cheap unlabelled data to provide a priori information required to ease under-determinism and reduce the sensitivity of inference to the input. The developed neural network model is tripartite, two of its ends are compressors that learn manifolds of interest in both input (captured data by the sensors) and output side (image) of the world. The first compressor uses large datasets of sensor data measured on a physical array. The data here does not need to be labeled. The second compressor uses simulated data with known permittivity distributions. A third module learns to connect the two earlier independently trained compressors using cheap unlabelled data. Lastly, a latent space calibration concept is introduced to enable the work on real-life data as the supervised training of the third module is performed on simulation data. The result is a stable solver with a high-resolution output.

Algorithm-VI: Image Fusion is used to combine the complementary information from different imaging algorithms, some of which are physics-based whereas others are data-driven, to generate a single combined output image.

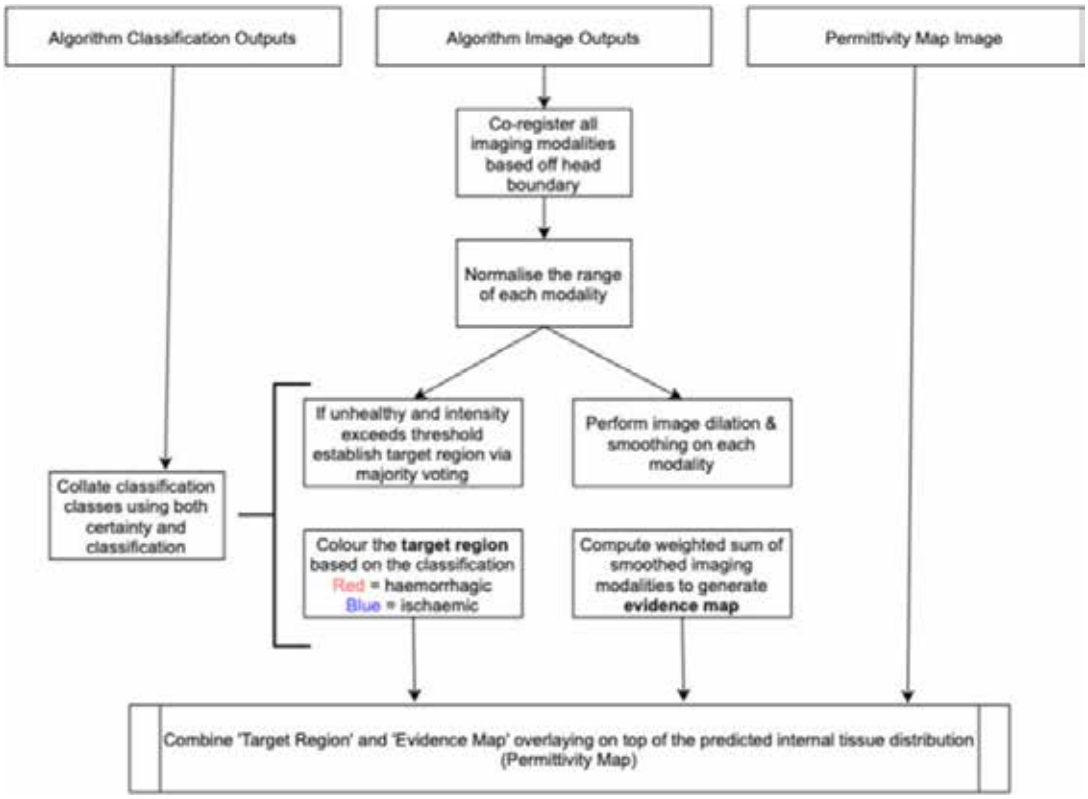


Fig. 7: Image Fusion is used to combine the complementary information from different imaging algorithms

Image fusion is used to combine the complementary information from different algorithms and generate the final image using the following steps: Co-registering different modalities into the same co-ordinates using an elastic warping algorithm, normalizing each modality to have the same intensity scale, finding the region of agreement between the algorithms by applying a threshold to the normalized images and returning the region of agreement based on the overlap. Each modality is then smoothed, and an image dilation operation is performed to produce closed-in and smooth target detection, and the region of agreement is superimposed on the smoothed modality outputs to generate the agreed target location as well as additional heatmap information provided from the different modalities. The final target location and heatmap are then colored based on stroke classification and superimposed on the neural network-based permittivity mapping output image.

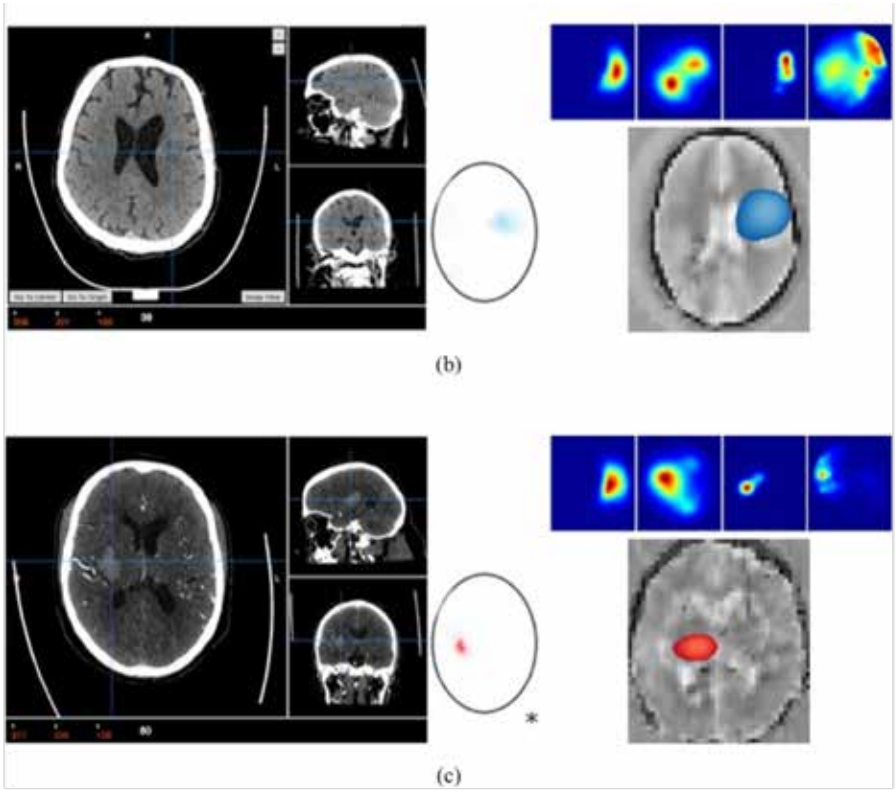


Fig.8: Shows the location and heatmap with color. Red color shows haemorrhage and blue color shows the ischaemic infarct

5. Clinical Applications of EMI

5.1 Neurological Disorders

- Epilepsy monitoring
- Parkinson's disease progression analysis

5.2 Psychiatric Conditions

- Depression and schizophrenia studies

5.3 Stroke and Trauma Diagnosis

- Identifying damaged brain areas for rehabilitation planning

6. Advantages and Limitations of EMI

6.1 Advantages

- Non-invasive and radiation-free
- Real-time and portable imaging capability
- High-resolution brain mapping

6.2 Limitations

- High cost and complex operation
- Sensitivity to artifacts and external noise
- Limited clinical validation compared to MRI and CT

7. Conclusion and Future Directions

EMI represents a significant advancement in non-invasive brain imaging, offering high accuracy in stroke detection. While challenges such as noise sensitivity and cost remain, ongoing research in hardware improvements and AI-driven algorithms can enhance its clinical adoption. Future work should focus on large-scale clinical trials to validate EMI's diagnostic potential and integration with other neuroimaging techniques.

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