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Mapping Activity Area Localization in Functional MRI Imaging with Deep Learning based Automatic Segmented Brain Tumor for Presurgical Tumor Resection Planning

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Abstract— Functional Magnetic Resonance Imaging (fMRI) determines small blood flow variations that arise due to brain activity. fMRI major study is about functional anatomy which determines the area of the brain controlling vital functions such as hand and foot motor movements for both left and right, speech mantra, and speech word activities. For this instinctive localization of activity areas for specific tasks is very important. This paper appropriately describes the fMRI paradigm timeline with a modified fMRI paradigm timeline due to the hemodynamic response function (HRF). Efficient activity area localization of thirty-three patients for fMRI data acquired from the hospital is achieved with dynamic thresholding. Dynamic thresholding is also effective in removing excess highlighted areas which helps in the reduction in expert efforts and time required to generate the patient report. The localize activity area is further mapped with deep learning-based automatic segmented brain tumor regions to find overlapping regions. The exact location of the overlapping region is recovered which helps with preoperative counseling and tumor resection planning. All the results are verified and validated by two expert radiologists from the Hospital.

Keywords- fMRI, BOLD, Eloquent Cortex, Presurgical Planning, Activity Area Mapping.

I. INTRODUCTION

According to the International Association of Cancer Registries (IACR), more than 28000 brain tumor patients reported and over 24000 are dying yearly in India [1]. A craniotomy is a common type of brain surgery. It is used to remove the whole tumor or part of the tumor, slowing down the tumor progression. In case of tumor is close in proximity to an important area that controls the main functions like movement, speech, and vision awake craniotomy is suggested. Awake craniotomy is a surgical procedure in which a patient is kept awake for part or the whole duration of surgery. During surgery, the patient is asked to speak or do movement for the tumor's mapping and resection. Thus, awake craniotomy is a complex procedure requiring the patient's phycological support and skilled anesthesiologists. For language function localization, it is necessary to find which part of the brain is responsible for avoiding damage. The invasive Wada test was used to make patients one side of the brain sleep using an anesthetic. Then the language side of the brain is determined by the patient's ability to answer a series of questions [2-3].

Functional Magnetic Resonance Imaging (fMRI) is a newly developed form of MRI to produce brain images. Non-invasive fMRI gives a far better view of brain functional images. To obtain functional information on a specific area, task-based fMRI is used. With the help of powerful magnetic fields and radio waves, MRI generates detailed images for examination of inner body structure. The magnetic field acts differently on oxygen-deficient hemoglobin and oxygenated hemoglobin [4-5]. These dissimilarities are used to map brain images to describe specific area activity known as blood oxygenation level-dependent (BOLD) imaging. But small variations in the blood flow of the cerebral system are used to generate images in fMRI to describe specific area activity making fMRI technically challenging. It can be used to locate brain areas for handling critical functions, assess the impact of stroke, or guide brain treatment for different disorders. In the task-based block design method, repeated active slots including specific tasks are separated by inactive slots. The eloquent cortex is the respective

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area in the brain responsible for a specific activity. Removal of the eloquent cortex makes sensory damage and can lead to paralysis. Using repetitive block design activity, eloquent cortex localization is done in presurgical patients. Using task-based fMRI abnormalities in the brain can be detected as well as compared to other imaging techniques which help in presurgical planning for a neurosurgeon. A major drawback is its interdisciplinary work which requires knowledge sharing in diverse fraternities.

This paper contributes:

- Significant and rare cases of data collection from the hospital over the duration of 9 years of fMRI images of brain tumor patients for the right and left hand as well as foot motor activity, both hand and foot motor activity, speech mantra, and speech word activity, followed by pre-processing steps for raw data acquired.
- A perfect interpretation of the fMRI paradigm for activity area localization for further analysis.
- Use of HRF for a modified algorithm for proper activity area detection.
- Dynamic thresholding for activity area detection and removal of excess highlighted areas from the resultant image.
- Deep learning-based automatic brain tumor segmentation from improved encoder-decoder architecture for obtained patients' images from the hospital.
- Mapping of detected activity areas with segmented tumor regions for finding overlapping regions for report generation which helps in preoperative tumor resection planning.

II. LITERATURE REVIEW

fMRI is mostly utilized to plan the preoperative removal of tumors from the eloquent cortex. A particular part of the brain that regulates crucial processes is called the eloquent cortex. Major focal nervous disparities are caused by eloquent cortex damage. The frontal lobe of the brain's primary motor cortex is a crucial region involved in carrying out voluntary motor movements. All sensory information from the body is received and processed by the primary somatosensory cortex, which is in the parietal lobe. The occipital lobe's primary visual cortex is a structure that is crucial for processing visual stimuli. The temporal lobe's primary auditory cortex, which processes auditory information, and Wernicke's area, which plays a key role in language development, are both located there. Language learning or usage may be significantly affected by damage to Wernicke's area of the brain. The frontal lobe area known as Broca's area is involved in speech production. Those who have experienced damage to this area of the brain struggle to talk, despite being able to understand language. [6].

A treatment strategy considering only MRI images is compared with a treatment strategy using a combination of MRI and functional MRI images. The brain tumor data from 21 patients are used in this study to evaluate the guidance of fMRI in presurgical treatment planning. Treatment modification is done in 7 out of 21 patients proving necessary information is provided by fMRI in mapping the eloquent cortex areas. Short and clinically feasible protocols consisting of 3-4 paradigms are designed. Realignment is used as motion correction in T2* weighted functional images. The general linear model was used for statistical parametric mapping. The activation area is calculated by subtracting the contrast of resting state images from active state images. The distance between tumor borders and different functional activity areas is calculated and classified into four conditions [7].

Eighty-seven glioma patients over a period of ten years with tumors located inside or in the near vicinity of the eloquent cortex were considered for this evaluation. For cortical mapping, preoperational functional MRI, and during tumor surgery, direct cortical stimulation (DCS) was performed. The region of interest using fMRI and DCS was evaluated and compared for the sensory-motor cortex, visual cortex, and language. Proves fMRI as a very well-precise preoperative approach for sensory motor tapping as compared to the visual cortex and language mapping [8].

A unique visual-triggered finger movement task (VFMT) is used and compared with the finger tapping task (FTT). Twenty glioma patients underwent presurgical fMRI mapping using block-designed FTT as well as VFMT and during tumor surgery, direct electrical stimulation (DES) was performed. New VFMT proves to be better as compared to FTT using intraoperative DES. SPM12 is used for second-level fMRI analysis to find the neuronal difference between the two tasks. Activation maps obtained from VMFT prove to be better in finding differences between tumor and eloquent cortical areas [9].

A reliability check on task-based fMRI for presurgical planning is done through a study on six low-grade tumors (LGG) patients, six high-grade tumors (HGG) patients, and twelve healthy controls using motor and language tasks. Reliability found is comparatively lower in HGG-affected as compared to LGG-affected and healthy controls. The study concludes fMRI is an appropriate means for presurgical planning with low-grade glioma patients. Spatial overlap, brain movement displacement, BOLD signal stability, and the Laterality index were used to find reliability [10].

Presurgical fMRI mapping is proved beneficial by assessing morbidity after tumor surgery in patients by using functional mapping prior to surgery with other advanced imaging techniques against standard neuronavigation. With appropriate

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analysis over a large database acquired from 1946 to 2020, sixty-eight patients were observed as eligible for further study [11].

III. DATA AQUISITION

A. Data Collection

Very rare and limited functional MRI data images of 53 brain tumor patients were acquired from Nanavati Max Super Speciality Hospital, Mumbai over a period from 2014 to 2022. Data is allowed to acquire as a part of a study in finding the feasibility and efficacy of functional MRI for presurgical brain mapping by the ethical committee of the hospital is an extremely challenging and time-consuming task. Images are captured using a GE Discovery 750W 3Tesla machine. Fig. 1, provides a visualization of data samples of a patient scan during one phase out of 104 phases of fMRI image acquisition.

B. fMRI Paradigm

A well-designed paradigm is essential to the success of an overall fMRI investigation. A typical fMRI generates enormous amounts of structural and functional data. For planning fMRI experiment a balance must be maintained for adequate spatial and temporal resolution. Temporal resolution determines how quickly each image is acquired. So, it is an approach for finding time separation in brain events. The task consists of a total of 104 phases of 3 seconds each. Each phase constitutes one complete scan covering the entire brain. Approximately 14 to 34 slices are captured in each phase. Fig. 2, is an example showing 20 scans required to complete one scan with yellow color lines. The number of slices per scan varies case to case basis. Considering a minimum of 20 slices per complete scan gives a total of 2080 slices or images through 104 phases in a 5-minute and 12-second event as shown in Fig. 3. During capture, the first 4 phases are given as relaxation time. The event starts with 10 phases of activity followed by 10 phases of the rest of 30 seconds each as illustrated in Fig. 4. A denotes the activity period and R

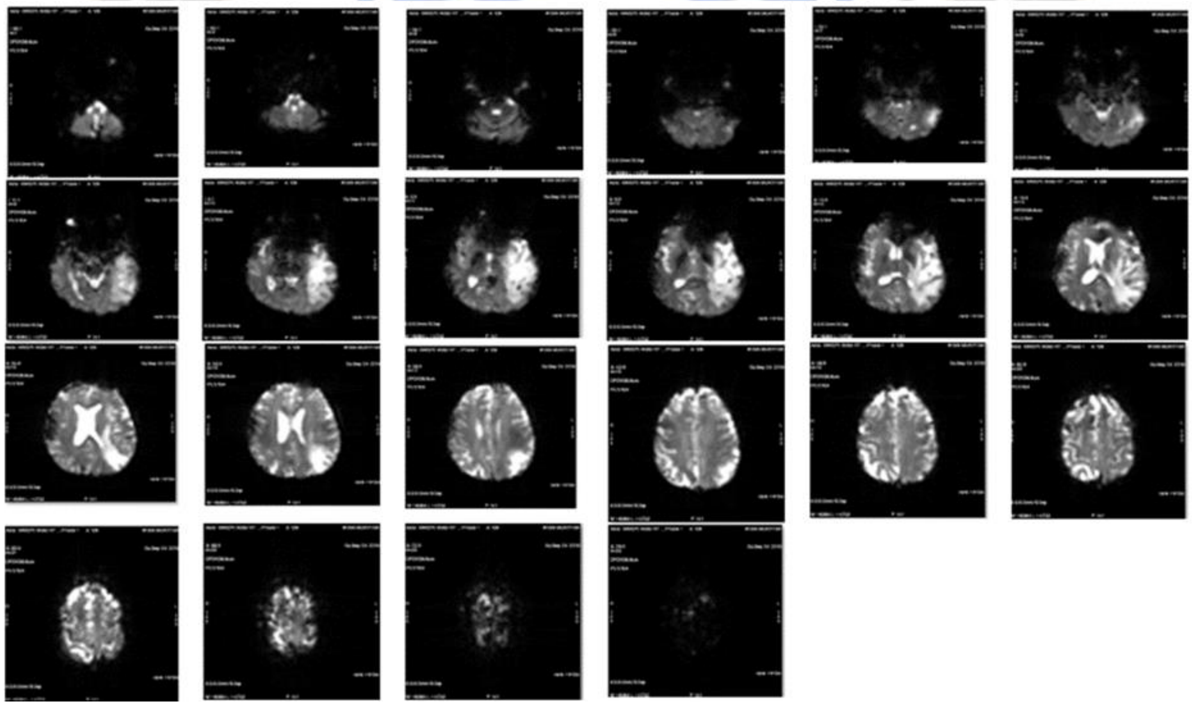

Figure. 1 Visualization of data samples during one phase scan of fMRI image acquisition.

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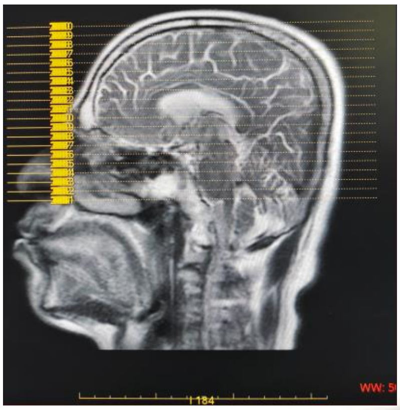

Figure. 2 Visualization of the scanning process

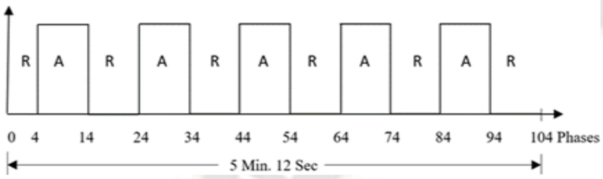

Figure. 3 fMRI paradigm timeline

denotes the rest period in the figure. The process is repeated and completed after 5 activities and 5 rest slots. The same process is repeated two to three times to make the patient comfortable with the given activity for better scans.

Different activities are assigned to patients depending on the location of the tumor region as per guidelines given by experts. Mainly Right-hand motor, Left-hand motor, Right Leg motor, Left Leg motor, both-hand and both-leg motor, Speech Mantra, and Speech Word activities are given to patients for specific area activity detection. Tapping of the thumb on the rest of the fingers during the activity period and no activity during the rest period is designed for right and left-hand motor activity. Dorsi flexion and plantar flexion movements of the forefoot during the activity period and no activity during the rest period is assigned during Right and left Leg motor activity. The same is done simultaneously for both hand and both leg activity. Any Mantra chanting is given during the activity period and no activity during the rest period of the speech mantra activity. From the given alphabet different pictures need to be imagined in the activity period and no activity during the rest period is designed for the speech word paradigm. In this paper, these activities are considered for analysis. Various other activities can be designed depending on tumor location by experts with their knowledge.

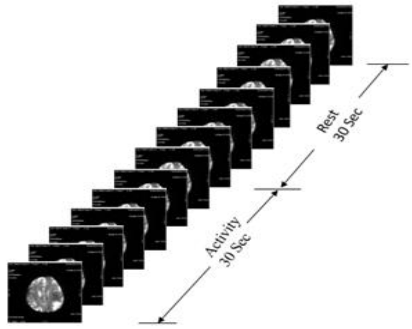

Figure. 4 Evaluation of fMRI paradigm

IV. METHODOLOGY

A. *Data Preprocessing*

Data acquired consists of a repeated series of multiple tasks. First, different tasks executed for patients need to be identified, and separate out the data for the respective task. In repeated series of the same task, later series is chosen from the understanding that practice makes the patient more perfect towards execution of the respective task. The varying number of scans required for different patients to cover the entire brain. Depending on the number of scans in one phase, images during relaxation time need to be discarded. When the number of scan images in the series is not matching with the fMRI paradigm timeline, such patients' data is discarded from the evaluation process. So, 33 patients' data is selected for further analysis.

B. *Activity area detection considering Hemodynamic response function (HRF)*

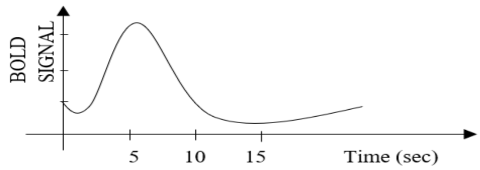

Figure. 5 Hemodynamic Response Function

Blood oxygenation level-dependent (BOLD) imaging is utilized to produce pictures in functional MRI. In response to a task, a particular area of the cerebral cortex boosts its activity. Which increases the extraction fraction of oxygen from the local capillaries. At that instant, this increases carbon dioxide and deoxygenated hemoglobin and decreases oxygenated hemoglobin. Paramagnetic properties of oxygenated hemoglobin and deoxygenated hemoglobin vary due to which the change is detected using fMRI [12]. The HRF in the BOLD signal appears after a 2 to 6-second delay as illustrated in Fig. 5. So, a modified fMRI paradigm timeline is shown in Fig.6, where Activity and Rest images are evaluated by delaying with one phase of three seconds.

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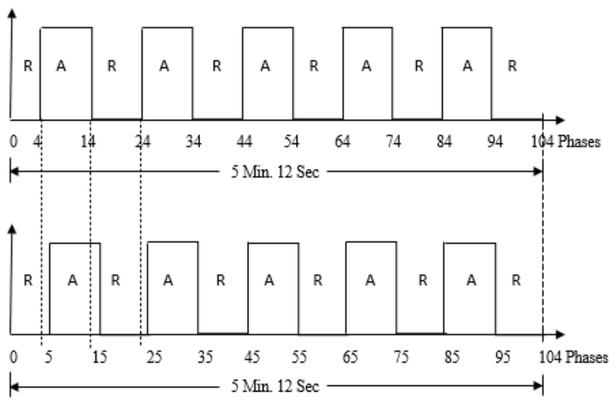

Figure. 6 Modified fMRI paradigm timeline

Automatic activity area detection is difficult for a deceased patient due to less concentration or difficulty in doing a specific activity as compared to the normal subject. fMRI data is acquired for a brain tumor patient. So, the images received consist of a BOLD signal for activity as well as the tumor in images. It is very difficult to segment only the activity area from an image consisting of a tumor in an image. Python programming is used to write and execute code on Google Colaboratory. For data visualization, matplotlib is used while cv2 library is used for the execution of image processing techniques. SciPy and Ipython are utilized for multidimensional array framework on top of NumPy framework and for data-intensive computing respectively. The following are the steps executed to find activity areas from fMRI images.

- Pixelwise intensity addition (PA) is performed separately on all activity images and the rest images from the selected series. Eq. (1), calculates activity image ASL1 for the first activity slot. Where n denotes the number of scans in one phase. Similarly, activity images for slot 2 to slot 5 are calculated using Eq. (2) to Eq. (5) respectively. The resultant activity image denoted by RA is calculated by adding all slot-wise activity images using Eq. (6). Same process is repeated to calculate the resultant rest image denoted by RR using Eq. (7) to Eq. (12)

$$ASL1 = PA\,[(n \times 5) + 1 \text{ to } (n \times 15)] \quad (1)$$

$$ASL2 = PA\,[(n \times 25) +1 \text{ to } (n \times 35)] \quad (2)$$

$$ASL3 = PA\,[(n \times 45) +1 \text{ to } (n \times 55)] \quad (3)$$

$$ASL4 = PA\,[(n \times 65) +1 \text{ to } (n \times 75)] \quad (4)$$

$$ASL5 = PA\,[(n \times 85)+1 \text{ to } (n \times 95)] \quad (5)$$

$$RA=PA[ASL1+ASL2+ASL3+ASL4+ASL5] \quad (6)$$

$$RSL1 = PA\,[(n \times 15) + 1 \text{ to } (n \times 25)] \quad (7)$$

$$RSL2 = PA[(n \times 35) + 1 \text{ to } (n \times 45)] \quad (8)$$

$$RSL3 = PA[(n \times 55) + 1 \text{ to } (n \times 65)] \quad (9)$$

$$RSL4 = PA[(n \times 75) + 1 \text{ to } (n \times 85)] \quad (10)$$

$$RSL5 =PA[(n \times 95) + 1 \text{ to } (n \times 104)] \quad (11)$$

$$RR= PA[RSL1+RSL2+RSL3+RSL4+RSL5] \quad (12)$$

- To find the eloquent cortex, the absolute difference between the resultant activity (RA)and resultant rest (RR) image is calculated. The generated resultant image is very much scattered, and experts need a lot of effort, skills, and time to convert that image for proper report generation.
- To overcome this problem a threshold needs to be set. Huge experimentation is carried out for setting up a threshold to find a proper eloquent cortex area. Depending on the difference value, the image value is set to 0 for below the threshold and to 255 for equal to and above the threshold. It is a tough task to define hardcoded threshold value as the difference between the addition of activity and the rest images converted to an array varies large case-to-case basis.
- Due to variations in activity performance person-to-person dynamic thresholding is necessary. The dynamic threshold is estimated for a patient using Eq. (13).

  $$\text{Dynamic Threshold} = \text{Constant} \times \text{Ref. Value} \quad (13)$$

  Where Ref. Value = Highest value in the resultant image and Constant = 0.3 to 9.7 is suggested by radiologists with the knowledge that activity performance varies between 30% to 97% from person to person.
- Multiple thresholds are experimented with to find different possible activity areas. Four different evaluations are compared in Fig. 7, using dynamic thresholding. T1, T2, T3 and T4 denote 0.3 × Ref. Value, 0.4 × Ref. Value, 0.5 × Ref. Value and 0.6 × Ref. Value respectively. As seen in the figure, for a lower threshold supplementary area comes under activity detection while for a higher threshold, a very less area is highlighted as an activity area. Under expert supervision, the threshold is set as 0.3 × Reference value or 0.4 × Reference which is represented by columns T1 and T2 respectively.

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- With the help of dynamic thresholding supplementary areas which are not required to highlight in the resultant image are reduced which helps in the reduction in expert efforts and time required to generate the patient report. This difference image represents activity areas in the image.

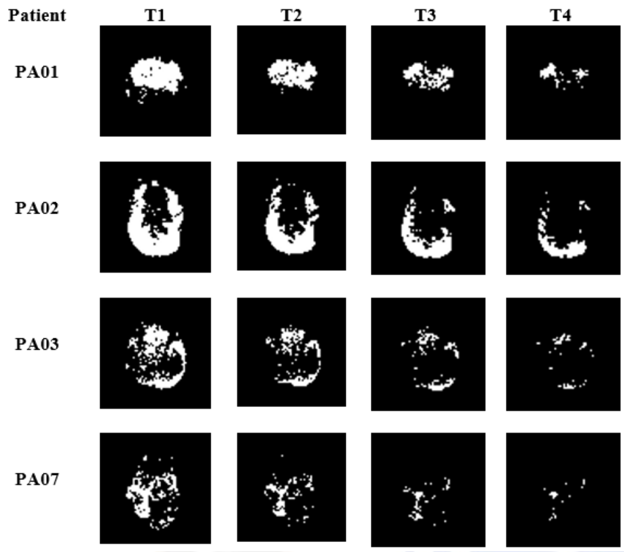

Figure. 7 Comparison of activity area detection for different patients with varying thresholds

C. *Deep Learning based Brain Tumor Segmentation*

Pre-operative 3D thin T1 weighted images were obtained for intra-operative neuronavigation through the brain from vertex to chin, without head tilt. The imaging protocol comprised a high-resolution BRAVO sequence. Time of echo (TE), 3.3 msec, flip angle of 12 degrees, matrix size, 256 × 215, slice thickness of 1 mm, slice space of 0 mm with a matrix size of 256 x 256. These images were obtained in DIACOM format.

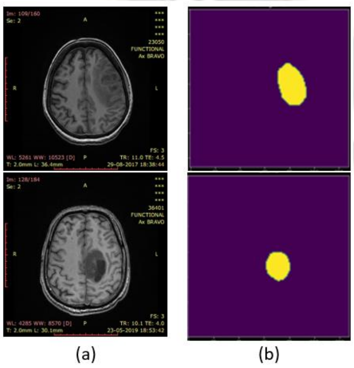

Figure.8 Visualization of automatic tumor segmentation a) Diacom images obtained from the hospital b) segmented brain tumor images using ResUnet2.

Deep learning-based architecture is built on Kaggle using Python programming language for automatic brain tumor segmentation [13]. The online available dataset on Kaggle is used for training [14]. For better generalization, various data augmentation techniques are used with random data splitting into training, validation, and testing sets. Transpose convolution is used for upsampling in a decoding layer which complements the encoding layer. ResUnet2 is implemented using an encoder-decoder architecture with ResNet 101 as a backbone architecture utilizing ADAM optimizer with 1e-4 as the learning rate is implemented. This model of 104 convolutional layers is used for the automated segmentation of Diacom tumor images acquired from the hospital as illustrated in Fig. 8.

V. RESULTS AND DISCUSSION

A. *Mapping of Localized activity area with a segmented brain tumor area*

To find an overlapping region pixel-wise comparison of the segmented tumor image and activity localized image is done. Fig. 9 illustrates the flow of mapping the tumor region and activity area to find overlapping regions for both overlapping and nonoverlapping instance for specific activity. For better visualization, the overlapping area is highlighted in red color, the non-overlapping tumor area in green, and the non-overlapping activity area in white. Table 1 shows a sample of tumor and activity area mapping for a few patients with their details from the complete study. From the table, it can be observed that different shapes and sizes of tumors are automatically segmented and mapped activity regions for various activities. Multiple activity regions can be detected and mapped with segmented tumor regions for a patient as shown in the table for PA22. Depending on the tumor location, experts suggest required activity functional MRI. Overlapping area removal in tumor resection surgery affects the respective activity performance of the patient after surgery. So, these results are very important in presurgical planning. These results are further used for report generation.

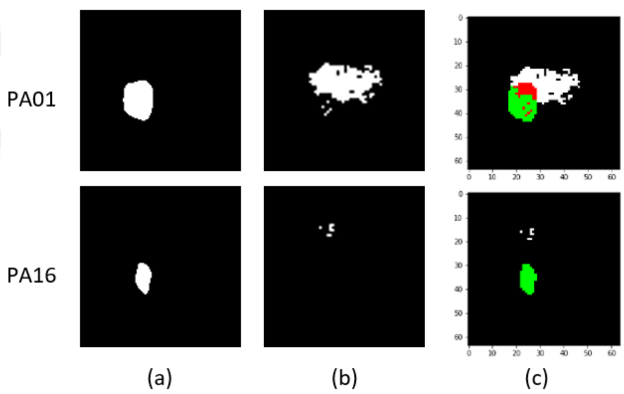

Figure. 9 Flow of Mapping activity area with the segmented tumor for overlapping and nonoverlapping instances: a) segmented tumor image b) activity area localization c) overlapping tumor area with activity region highlighted with red color, non-overlapping tumor and activity with green and white color respectively.

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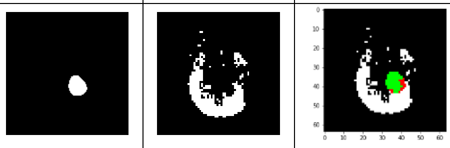
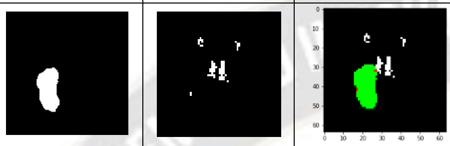
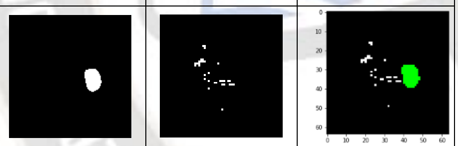
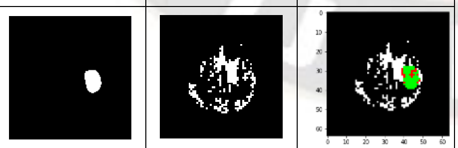
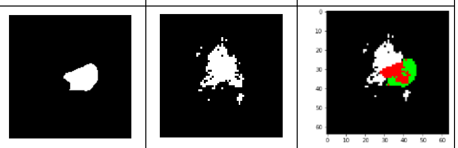
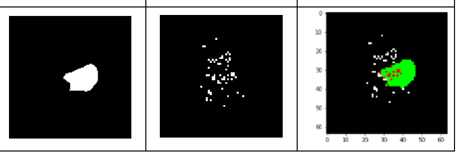
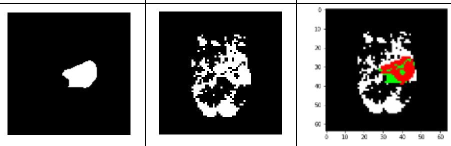
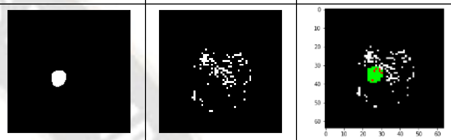
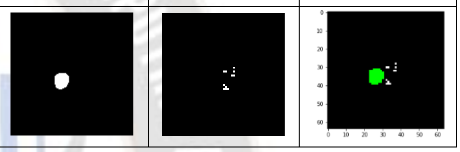
TABLE I. Mapping of tumor and activity region.

Patient Details	**Output at Different Stages**			
	Task	***Tumor***	***Activity***	***Mapped Image***
PA02 N=18 1872 Scans	RT Hand motor			
PA03 N=18 1872 Scans	RT Hand motor			
PA08 N=20 2080 Scans	LT hand motor			
PA10 N=22 2288 Scans	RT hand motor			
PA15 N=14 1456 Scans	Speech Mantra			
PA18 N=23 2392 Scans	RT Hand Motor			
PA22 N=18 1872 Scans	Speech Mantra			
	RT hand Motor			
	Speech Word			
PA24 N=24 2496 Scans	RT Hand Motor			
	RT Foot Motor			
	Speech			
PA27 N=20 2080 Scans	LT Hand Motor			
	LT Foot Motor			
PA32 N=24 2496 Scans	LT Hand Motor			
	Speech Mantra			

B. Report Generation

A report is generated based on whether overlapping is observed or not as shown in Fig. 10. When extracted activity area is overlapped with an automatically segmented brain tumor region, the report is generated as shown in Fig. 10(a). Here overlapping pixel coordinates are also extracted. And when there is no overlap, the report is generated as shown in Fig.10(b). Overlapping present or not is very useful in planning brain tumor surgery.

```
37 39
37 40
38 40
39 40
39 41
41 40
42 35
activity area overlaps on tumor region
```

(a)

```
No Overlapping observed
```

(b)

Figure.10: Report generation after mapping activity area with tumor region in case of
(a) overlapping observed with overlapping pixel coordinates,
(b) no overlapping observed.

VI. CONCLUSION

Neurosurgeons need to have an accurate picture of the patient's viscera prior to brain surgery for the removal of abnormal tissue or tumor. Functional magnetic resonance imaging (fMRI), a method prior to invasive surgeries, serves this purpose. This paper describes the fMRI paradigm timeline with various activities, which helps other researchers contribute to this emerging area. Data acquired for hand and leg motor activity, both hand, and both leg motor activity, Speech Mantra, and Speech Word activity is localized using dynamic thresholding considering hemodynamic response function delay. Dynamic thresholding has proved to be useful in removing excess highlighted areas in images which reduce the efforts and time required of expert radiologists. The extracted activity area is mapped with an automatically segmented brain tumor area using deep learning-based ResUNet2 architecture to find the overlapping region of the tumor with the detected activity region. Based on the mapping, the report is generated with overlapping pixels' exact location which helps neurosurgeons in proper presurgical tumor resection planning. The complete process and results are verified and validated by two expert radiologists from the hospital.

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