Combination of Structural and Functional MRI with Rapid Prototyping as a Neurosurgical Tool

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Introduction: Rapid prototyping (RP) uses an additive manufacturing to generate a 3D physical model of an object from a finite element mesh defining the surface of the object. This work presents methods to adapt MRI data to create RP scale models of a subject's brain showing important structural and functional regions relative to a tumour. The technique may prove useful for neurosurgical planning.

Methods: A patient with a tumour in the left sensorimotor cortex was scanned using a 3T MRI scanner (Magnetom Allegra, Siemens Medical Solutions, Erlangen, Germany). Structural imaging was done using a 3D T1-weighted MPRAGE sequence [1] with TR = 2300 ms, TE = 3.93 ms, TI = 1100 ms, flip angle = 9 degrees, spatial resolution = 1×1×1mm^3, matrix size = 256×256, slices = 260, FOV = 250 mm, scan time = 9:50. Functional MRI (fMRI) data were acquired using an EPI BOLD sequence with TR = 2000 ms, TE = 30 ms, slices = 34, spatial resolution = 3.8×3.8×3.5mm^3, matrix size = 64×64, FOV = 240, measurements/volumes = 121, scan time = 4:06. Separate tasks were performed to map motor function for the patient's right hand and right foot. Contra-lateral comparative fMRI data were also obtained for the patient's left hand and left foot. Each task involved 30 second interleaved periods of rest and activity.

The fMRI statistical maps were extracted ($p < 0.05$) and the first EPI volume was co-registered to the MPRAGE image. The MPRAGE image was then classified into grey matter, white matter and CSF. These pre-processing steps were performed using the FSL (FMRIB, Oxford) and SPM8 (Welcome Trust Centre for Neuroimaging, London) packages. The white matter and CSF volumes were then discarded for several reasons: only the pial surface is required to identify landmarks; the fMRI regions are limited to the grey matter; and the amount of material used in the RP process should be minimized to save printing costs. The tumour was segmented using an adaptive region growing algorithm.

To visualise the tumour and the inside of the brain, the remaining volume was separated into two portions based on the tumour position and the relative position of the fMRI statistical maps. Each portion was converted to a binary volume and meshed using a marching cubes algorithm. These steps were implemented using custom tools written in C++. Thereafter, clustering decimation and Laplacian smoothing was performed using MeshLab (Visual Computing Lab, Pisa, Italy), and mesh repair was performed using 3Data Expert (DeskArtes, Espoo, Finland) and VRMesh (VirtualGrid, Seattle, WA). This repair involved removing duplicated, intersecting and non-manifold triangles, and closing gaps in the mesh.

The model was then printed (Z510 Spectrum 3D printer). The total time taken to print was approximately 12 hours and the cost was approximately US$ 360.

The accuracy of the model will be subject to several sources of error. These include the MR scanner and sequence (e.g. B0 and B1 distortions), the segmentation, the meshing, and the printing. The accuracy was evaluated by acquiring an MPRAGE image of the printed models submerged in a tank of water, using the same scan parameters as above. These were inverted and co-registered to the binary images used to create the mesh. A voxel-wise comparison was made to quantify the accuracy of the RP model.

B0 and B1 distortions were estimated using the scanner B1 field parameters [2] and multi-echo phase maps [3] to see if they had a significant effect on the accuracy of the model.

Results: Figure 1 shows the difference between to actual and the printed brains. The most prominent errors correspond to subcortical sealed cavities that were not filled with water when the model was scanned. The surface of the brain is of primary interest so subcortical voxels can be ignored when calculating the accuracy. Limiting the assessment to thin plate-like volumes by ignoring volumes larger than 5x5x5 mm^3, the accuracy of the model was found to be 84.96%. The maximum gradient field distortion was 2-3mm and the maximum B0 distortion was 0.152 mm.

Figure 2 shows the RP model, where the tumour and fMRI regions have been marked manually. The sulci are still clearly apparent, indicating that unnecessary dilation has not taken place.

Conclusion: This study demonstrates the feasibility of producing a RP model of the brain from structural and functional MRI data. This provides a hands-on physical model which may assist neurosurgical planning by giving an intuitive indication of the depth and extent of the tumour, and by providing clear reference landmarks on the surface of the brain. The accuracy of the model has been quantified, and errors due to magnetic field distortions were shown to be small compared to the dimensions of the brain. Further work will involve integrating the process into a single software package, printing using coloured and transparent materials, and reducing the costs of the printing.

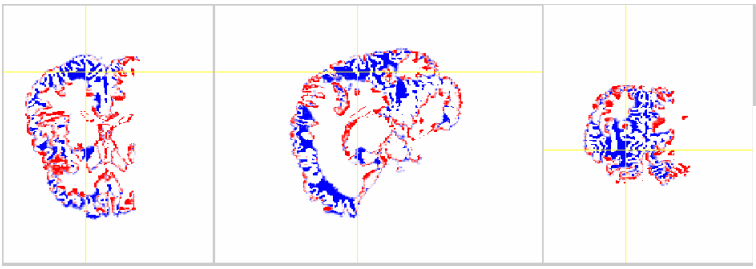

Figure 1: Difference between the planned and printed brains. The blue shows the voxels in the model that were not in the real brain and the red shows the voxels in the real brain that were not present in the model.

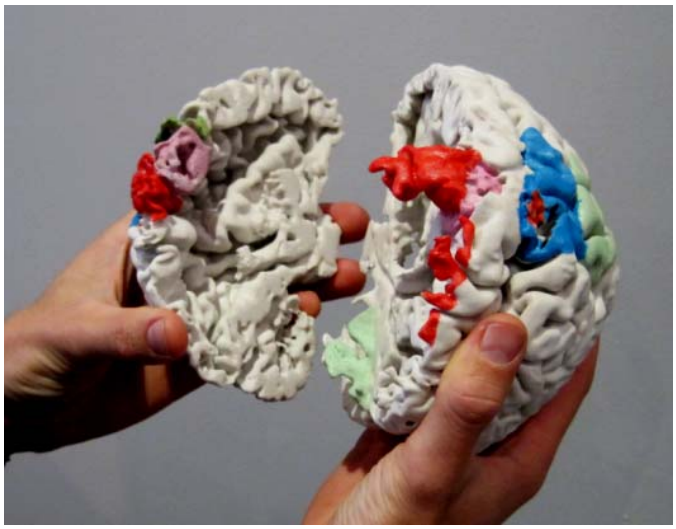

Figure 2: Rapid prototype model showing both structural and functional MRI features relative to a tumour. The tumour is shown in pink. Regions of activation identified using functional MRI are as follows: red – right hand; blue – left hand; green – left foot.

References:

1. Mugler and Brookeman MRM 1990; 15(1):152-7.
2. Janke et al. MRM 52:115-22.
3. Jezzard and Clare HBM; 8:80-5.

Acknowledgements:
Siemens Medical Solutions, South Africa