Intraoperative overlay of optic radiation tractography during anteromesial temporal resection: a prospective validation study

Vejay N. Vakharia, PhD, FRCS(SN),1,2 Sjoerd B. Vos, PhD,3 Gavin P. Winston, BM BCh, PhD,1,2,4 Matthew J. Gutman, MBBS,2 Victoria Wykes, MB, PhD,6,7 Andrew W. McEvoy, MD,1,2 Anna Miserocchi, MD,1,2 Rachel Sparks, PhD,8 Sebastien Ourselin, PhD,8 and John S. Duncan, MA, FRCP, FMedSci1,2

1Department of Clinical and Experimental Epilepsy, University College London and Epilepsy Society MRI Unit, London; 2National Hospital for Neurology and Neurosurgery, Queen Square, London; 3Wellcome/EPSRC Centre for Interventional and Surgical Sciences, University College London, United Kingdom; 4Department of Medicine, Division of Neurology, Queen’s University, Kingston, Ontario, Canada; 5Alfred Health, Melbourne, Australia; 6Institute of Cancer and Genomic Sciences, University of Birmingham; 7Department of Neurosurgery, Queen Elizabeth Hospital, Birmingham; and 8School of Biomedical Engineering and Imaging Sciences, St Thomas’ Hospital, King’s College London, United Kingdom

OBJECTIVE Anteromesial temporal lobe resection (ATLR) results in long-term seizure freedom in patients with drug-resistant focal mesial temporal lobe epilepsy (MTLE). There is significant anatomical variation in the anterior projection of the optic radiation (OR), known as Meyer’s loop, between individuals and between hemispheres in the same individual. Damage to the OR results in contralateral superior temporal quadrantanopia that may preclude driving in 33%–66% of patients who achieve seizure freedom. Tractography of the OR has been shown to prevent visual field deficit (VFD) when surgery is performed in an interventional MRI (iMRI) suite. Because access to iMRI is limited at most centers, the authors investigated whether use of a neuronavigation system with a microscope overlay in a conventional theater is sufficient to prevent significant VFD during ATLR.

METHODS Twenty patients with drug-resistant MTLE who underwent ATLR (9 underwent right-side ATLR, and 9 were male) were recruited to participate in this single-center prospective cohort study. Tractography of the OR was performed with preoperative 3-T multishell diffusion data that were overlaid onto the surgical field by using a conventional neuronavigation system linked to a surgical microscope. Phantom testing confirmed overlay projection errors of < 1 mm. VFD was quantified preoperatively and 3 to 12 months postoperatively by using Humphrey and Esterman perimetry.

RESULTS Perimetry results were available for all patients postoperatively, but for only 11/20 (55%) patients preoperatively. In 1/20 (5%) patients, a significant VFD occurred that would prevent driving in the UK on the basis of the results on Esterman perimetry. The VFD was identified early in the series, despite the surgical approach not transgressing OR tractography, and was subsequently found to be due to retraction injury. Tractography was also used from this point onward to inform retractor placement, and no further significant VFDs occurred.

CONCLUSIONS Use of OR tractography with overlay outside of an iMRI suite, with application of an appropriate error margin, can be used during approach to the temporal horn of the lateral ventricle and carries a 5% risk of VFD that is significant enough to preclude driving postoperatively. OR tractography can also be used to inform retractor placement. These results warrant a larger prospective comparative study of the use of OR tractography–guided mesial temporal resection.


KEYWORDS tractography; optic radiation; Meyer’s loop; epilepsy; surgical technique

ABBREVIATIONS ATLR = anteromesial temporal lobe resection; FA = fractional anisotropy; FOD = fiber orientation distribution; ILAE = International League Against Epilepsy; iMRI = interventional MRI; LGN = lateral geniculate nucleus; OR = optic radiation; VFD = visual field deficit.


INCLUDE WHEN CITING Published online July 30, 2021; DOI: 10.3171/2020.12.JNS203437.
ANTEROMESIAL temporal lobe resection (ATLR) has been shown to provide durable seizure-free remission in over two-thirds of patients with drug-resistant epilepsy due to mesial temporal sclerosis.\textsuperscript{1,12} Numerous surgical approaches have been described, including selective approaches that incorporate transylvian, transcortical, and subtemporal approaches, as well as more standardized approaches that involve resection of the temporal pole and variable amounts of the temporal neocortex.\textsuperscript{3,4} Each of these approaches has its respective benefits and limitations. Chief among the limitations is the associated risk of visual field deficit (VFD), as well as other neurological and psychological sequelae.\textsuperscript{5–7} There remains uncertainty whether one approach is superior to another despite previous randomized controlled trials and meta-analyses,\textsuperscript{8–11} with one study advocating use of ATLR on the language-dominant hemisphere and selective approaches on the nondominant hemisphere.\textsuperscript{12} Due to the intimate anatomical relationship of the optic radiation (OR) to mesial temporal structures,\textsuperscript{13} overall VFD is reported in as many as 50%–100% of patients.\textsuperscript{14–16} In contemporary series of transylvian approaches, VFDs are large enough to preclude 66% of patients from retaining a driving license when considered with postoperative seizure freedom.\textsuperscript{17,18} In contrast, modified ATLR techniques that incorporate temporobasal approaches to the temporal horn have shown VFD rates as low as 4%,\textsuperscript{19} highlighting the importance of the surgical approach.

Previous studies have shown the benefits of OR tractography for identifying Meyer’s loop.\textsuperscript{20–22} These studies have shown considerable variation in the anterior extent of Meyer’s loop, which ranges from 22 to 37 mm in anatomical studies\textsuperscript{23} and from 24 to 47 mm in tractography studies\textsuperscript{22} when measured from the temporal pole. In addition to variation between patients, there is also asymmetry between the language-dominant and nondominant hemispheres, as identified with functional MRI lateralization indices, with Meyer’s loop projecting more anteriorly in the language-dominant hemisphere.\textsuperscript{24} Although direct intraoperative visualization of the optic pathway is not possible currently, probabilistic reconstructions of estimated water movement with diffusion-weighted imaging have been used successfully to represent the OR during ATLR and to limit VFD, thus allowing patients to retain a driving license if they are seizure free postoperatively.\textsuperscript{20} These studies, however, required the use of an interventional MRI (iMRI) suite with an intraoperative scan after lateral neocortical resection. This adds not only to the duration of the procedure but also to the cost, and access to an iMRI suite is not widely available. Previous studies that utilized iMRI have also shown that the amount of brain shift in the anteroposterior axis is negligible, with a mean displacement of 0.5 mm; this suggests that intraoperative scanning may not be required.

We aimed to utilize preoperative multishell 3-T probabilistic tractography in a conventional operating theater. In combination with a neuronavigation system and an operative microscope, we first performed a phantom study to determine the accuracy of the overlay projection. Second, we developed a process to incorporate this overlay into clinical workflow, and we performed a prospective clinical study to overlay the tractographic representation of the OR onto the brain during ATLR surgery and to determine the rate of VFD due to use of this technique.

**Methods**

The article was prepared in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement for cohort studies.\textsuperscript{25} For the first study, we identified a patient who had previously undergone ATLR and in whom OR tractography was performed by using the techniques described below. A highly accurate 3D model of the patient’s scalp, cortex, corticospinal tract, and OR was created. The overlying middle temporal gyrus and precentral cortex were segmented separately, and the 3D model was printed by using selective laser sintering (3D Systems, Inc.). Metal screws were anchored into the 3D-printed model as fiducials, and then a volumetric CT scan was performed with 0.7-mm\textsuperscript{3} voxels. Preoperative T1-weighted MRI and phantom CT images were registered and fused by using the neuronavigation system (StealthStation S7, Medtronic Inc.). The model was fixed to the operating table by using a Mayfield clamp and subsequently registered to the neuronavigation system with a calculated registration error of 0.8 mm. The neuronavigation system was connected to the operative microscope (Zeiss OPMI Pentero 800, Karl Zeiss Meditec AG), and the tractographic overlays of the corticospinal tract and OR were visualized in the occulors. The projection error overlaying the anterior aspect of the OR (Meyer’s loop) was then measured by using digital calipers from several surgically relevant directions (Fig. 1).

In the second study, we performed an open-label prospective single-arm clinical study (between May 2017 and May 2019) to identify the risk of VFD associated with intraoperative OR tractography. By using a prospective power calculation available in the literature that assumed a 30% incidence of VFD would preclude the patient from maintaining a driving license,\textsuperscript{16,26–28} we aimed to detect a 90% reduction in VFD in the study cohort based on a type I error rate of $\alpha = 0.05$, a type II error rate of $\beta = 0.1$, and power = 90%. By applying dichotomous endpoints of eligibility to drive versus ineligibility to drive, we required a total of 17 patients. To allow for dropouts, 20 patients were prospectively enrolled in the study. All patients provided written informed consent to participate in this study, which was approved by the National Research Ethics Service Committee London.

Patients were invited preoperatively and postoperatively (between 3 and 12 months) to undergo visual field assessment with the monocular Swedish interactive threshold algorithm (Central 30–2 SITA Fast) on an automated Humphrey perimeter, in which both eyes were tested independently, and with the binocular Esterman protocol at both time points. Before surgery, all patients underwent diffusion-weighted imaging as part of the routine preoperative epilepsy-imaging protocol at our center. Diffusion-weighted MRI data were acquired by using a single-shot echo-planar imaging readout with 2-mm isotropic resolution (TE/TR 74.1/7600 msec). A total of 115 volumes were scanned by using a multishell approach (11, 8, 32,
Results

The overlay of the OR segmentation was visible over the 3D-printed phantom through the microscope’s oculars and revealed a maximal combined registration and projection error of 1 mm when viewed from all surgically relevant directions and measured by using digital calipers. In combination with a 2-mm safety margin, this indicated that 3-mm dilation should be applied to OR tractography (Fig. 3) in the subsequent clinical study.

Twenty patients (9 underwent right-side ATLR, and 9 were male) with drug-refractory mesial temporal lobe epilepsy, with a median (range) age of 37.5 (21–60) years, were recruited to participate in the clinical study (see Table 1 for patient demographic characteristics and surgical outcomes).

After administration of general anesthesia, patients were fixed to the operating table by using a Mayfield clamp and registration to the neuronavigation system was performed by using skin fiducials. A curvilinear incision was made from the zygoma, approximately 1 cm anterior to the tragus, and extended superiorly and posteriorly to the level of the posterior pinna. The incision was then extended to the anterior hairline at the level of the superior temporal line. A myocutaneous flap was then raised, and craniotomy was performed to expose the temporal floor and pole as far anteriorly as possible. The dura mater was opened in a stellate fashion, and lateral neocortical resection included the superior, middle, and inferior temporal gyri, as well as the temporal pole. The posterior limit of lateral neocortical resection was 3.5 cm from the temporal pole. After resection of the temporal pole, the underlying white matter was not disturbed until the overlay projection had been applied (Fig. 4).

The temporal horn was then approached by utilizing a subtemporal approach through the collateral sulcus. After identification of the temporal horn, the uncal recess was divided and the amygdala was resected by utilizing a cor-

and 64 gradient directions with b values of 0, 300, 700, and 2500 sec/mm², respectively). A single image with a b value of 0 and reverse phase-encoding was also acquired for distortion correction. Diffusion data were corrected for scanner drift, eddy current–induced distortion, patient movement, and susceptibility-induced distortion by using FSL v5.10 eddy and top-up tools. Fiber orientation distributions (FODs) were estimated in each voxel by using multi-tissue constrained spherical deconvolution in MRtrix3. OR tractography was performed by deriving the lateral geniculate nucleus (LGN) as the seed region of the interest and by using the T1-weighted, fractional anisotropy (FA), and FOD overlays, as shown in Fig. 2. The axial plane was realigned with the anterior optic apparatus, such that the optic nerve, optic chiasm, and optic tract were all visible in the same slice. The LGN seed (3 × 3 × 2 voxels) was placed by using an combination of the anatomical location and the fiber orientation direction. An inclusion region of interest was placed in the ipsilateral stratum sagittale, and exclusion zones were placed at the midline to prevent reconstruction of commissural fibers within the cerebral peduncle to prevent propagation along the corticospinal tract, as well as at the temporal pole to eliminate the inferior longitudinal fasciculus and at the frontal pole to eliminate the inferior frontooccipital fasciculus. Streamline propagation was performed by utilizing second-order integration over the FOD probabilistic tractography algorithm (iFOD2).

A total of 5000 streamlines were generated for each patient. The corresponding representation of the OR was then binarized after application of a threshold to remove voxels with the bottom 5% of streamline densities. The binary map was then dilated by 3 mm (2 mm to account for registration errors and an additional 1 mm to account for overlay inaccuracy) and converted to the OR segmentation that had been uploaded to the neuronavigation system to provide intraoperative guidance, as shown in Fig. 3.
FIG. 2. Multiplanar reconstructions of the LGN seed region and derivation of the LGN seed for OR tractography. Upper: T1-weighted, FA, and T1-weighted images with FOD overlay are shown, as well as the LGN seed region (crosshair), in the axial, coronal, and sagittal planes. The left-right (red), anterior-posterior (green), and superior-inferior (blue) directions are shown.

Lower Left: FODs per voxel are shown overlaid onto the axial T1-weighted image of a patient who underwent axial plane reconstruction to align the axis of the optic nerve (A), optic chiasm (B), and optic tract (C) terminating in the LGN (D).

Lower Right: 3D representation of the FOD at the LGN seed region, showing the incoming optic tract (E) with the anterolaterally (F) and laterally (G) projecting fiber groups. A $3 \times 3 \times 2$ (X, Y, Z) region of interest is centered at this point. The left-right (red), anterior-posterior (green), and superior-inferior (blue) directions are shown. Figure is available in color online only.
the requirements for a Group 1 license. The single VFD was identified early in the series (patient 4), even though the surgical approach did not transgress OR tractography, and was subsequently found to be due to retraction injury (Fig. 5). Postoperative diffusion data confirmed low FA values in the area of the retraction injury that prevented streamline propagation through Meyer’s loop. Postoperatively, this patient achieved International League Against Epilepsy (ILAE) type 3 outcome and therefore would not have been eligible to hold a driving license in the UK from the point of view of seizure freedom. From this point onward, tractography was used to inform retractor placement and no further significant VFD occurred. Postoperative ILAE type 1A outcome, indicating complete seizure-free outcome and no auras at 12 months, was achieved in 65% (13/20) of patients.

### Discussion

We report that ATLR, performed by utilizing preoperative probabilistic tractography with application of appropriate distortion correction and error margin to account for registration and overlay errors in a conventional operating theater with a commercially available neuronavigation system and microscope, resulted in a 5% rate of significant VFD. The visual field requirements to hold a Group 1 driving license in the UK mandate no visual loss along the horizontal meridian over an area subtending 120° and no significant defect within the central 20° of the patient’s visual field when examined with the binocular Esterman protocol. A significant defect within the central visual field is defined as a single cluster of 4 or more contiguous points. Epilepsy surgery for drug-resistant mesial temporal sclerosis provides durable seizure freedom in approximately two-thirds of patients; however, despite achieving seizure freedom, patients may be ineligible to retain a driving license owing to the magnitude of VFD.

Several different surgical approaches have been described for amygdalohippocampectomy, including standardized, selective stereotactic radiosurgery, and laser interstitial thermal therapy. Selective approaches include transsylvian, transcortical, and subtemporal methods.
In an early series of patients treated with standard anterior temporal lobectomy, for which lateral neocortical resection was commonly extended to 6.5 cm in the nondominant hemisphere and 4.5 cm in the dominant hemisphere, VFD was considered unavoidable and expected. As microsurgical techniques have been progressively refined, the extent of lateral neocortical resection has been reduced to approximately 3.5 cm bilaterally and rates of significant VFD have subsequently declined. In comparison with transsylvian approaches, approach to the temporal horn from the base of the temporal lobe through the collateral sulcus, as performed with subtemporal resection and modern variations of standard anteromesial resection, was found to double the chance of a patient retaining a driving license postoperatively, from 33% (transsylvian group) to 66% (temporobasal group) in a prospective randomized controlled trial. VFD may occur through damage to the anterior aspect of the OR called Meyer’s loop or to the LGN, which lie superior to the hippocampus across the choroidal fissure. Damage to Meyer’s loop results in contralateral homonymous superior quadrantanopia, whereas damage to the LGN causes contralateral homonymous hemianopsia. The OR, also known as the geniculocalcarine tract, emerges from the LGN and forms the retrolenticular part of the internal capsule. The fibers subsequently fan over the roof of the temporal horn of the lateral ventricle in three discrete bundles before sweeping posteriorly to join the stratum sagittale on the lateral aspect of the atrium and occipital horn en route to the occipital lobe. Anatomical dissections, performed by utilizing Klingler’s method, have revealed that three discrete bundles arise from the LGN with fibers running anterolaterally (Meyer’s loops), laterally, and posteriorly. Meyer’s loop has been shown to have an intrinsic topology, with the most anteriorly projecting fibers subserving the superior-most aspect of the contralateral visual field. Therefore, we performed probabilistic tractography of the OR by placing a seed at the region of the LGN. The LGN was identified through a combination of anatomical landmarks and the FODs, as shown in Fig. 2, where the anterolateral and lateral fiber bundles are shown after the optic tracts were traced posteriorly. An inclusion region of interest was placed at the stratum sagittale and exclusion zones were placed in the contralateral hemisphere, at the temporal pole and in the frontal white matter. Despite use of inclusion and exclusion regions, probabilistic tractography still results in some spurious streamlines. To mitigate these errors, and in accordance with the results of other

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age (yrs)/Sex</th>
<th>Side</th>
<th>Language Dominance*</th>
<th>MRI Findings</th>
<th>Preop SEEG</th>
<th>Histology</th>
<th>ILAE Type at 12 mos</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21/F</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>2</td>
<td>42/F</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>Yes</td>
<td>ILAE type 3 hippocampal sclerosis</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>26/M</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>4</td>
<td>60/M</td>
<td>Lt</td>
<td>Bilat</td>
<td>Lt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>36/M</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis</td>
<td>Yes</td>
<td>ILAE type 2 hippocampal sclerosis</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>59/M</td>
<td>Rt</td>
<td>Bilat</td>
<td>Rt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 2 hippocampal sclerosis</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>33/F</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis &amp; Lt temporal dygenesis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>8</td>
<td>31/M</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis</td>
<td>Yes</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>9</td>
<td>35/M</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>10</td>
<td>55/M</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis &amp; focal cortical dysplasia type IIIa</td>
<td>1A</td>
</tr>
<tr>
<td>11</td>
<td>59/F</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>12</td>
<td>40/F</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>Yes</td>
<td>Chronic scar tissue w/o evidence of cortical malformation or hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>13</td>
<td>47/F</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis &amp; bilat frontal lobe heterotopias</td>
<td>Yes</td>
<td>ILAE type 3 hippocampal sclerosis</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>49/F</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis</td>
<td>Yes</td>
<td>ILAE type 2 hippocampal sclerosis</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>32/F</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 2 hippocampal sclerosis</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>23/M</td>
<td>Lt</td>
<td>Lt</td>
<td>No structural abnormalities</td>
<td>Yes</td>
<td>Mild mossy fiber sprouting w/o evidence of cortical malformation or hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>17</td>
<td>38/F</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>18</td>
<td>37/F</td>
<td>Rt</td>
<td>Lt</td>
<td>Rt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>19</td>
<td>38/F</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 2 hippocampal sclerosis</td>
<td>1A</td>
</tr>
<tr>
<td>20</td>
<td>32/M</td>
<td>Lt</td>
<td>Lt</td>
<td>Lt hippocampal sclerosis</td>
<td>No</td>
<td>ILAE type 1 hippocampal sclerosis</td>
<td>1A</td>
</tr>
</tbody>
</table>

SEEG = stereoelectroencephalography.
* Determined with functional MRI.
studies in the literature, the bottom 5% of streamline densities were removed. In comparison with deterministic algorithms, this approach is most consistent with postmortem white fiber dissections performed with Klingler’s method and is also capable of predicting postoperative VFD. 21, 43

There is significant between-patient variability in the anterior extent of Meyer’s loop, as defined by the distance from Meyer’s loop to the temporal pole; however, in all cases, anatomical dissection showed that Meyer’s loop projected anteriorly to the temporal horn. 44 Additional studies that combined tractography and functional MRI to derive language lateralization indices have also revealed that Meyer’s loop extends more anteriorly in the language-dominant hemisphere. 24 During standard ATLR, Meyer’s loop is susceptible to damage during approach to the amygdala and temporal horn. Selective approaches, such as the subtemporal approach, allow access to the temporal horn from the base of the brain through the collateral sulcus, and these are less likely to damage Meyer’s loop without compromising seizure-freedom rates. Other selective approaches, such as the transsylvian approach, necessitate superior access to the temporal horn through the temporal stem; therefore, these approaches are more likely to result in a significant VFD. 18

Because the OR is not visible during surgery, there is no in vivo gold standard for comparison with our technique, and the OR cannot be visually distinguished from other white fiber tracts within the temporal stem, such as the uncinate and inferior frontoorbital fasciculi, or temporal white matter, such as the inferior longitudinal fasciculus. Several groups have reported using intraoperative tractography to minimize rates of VFD during ATLR. 20, 43, 45, 46 A major limitation of using neuronavigation systems to define the location of the OR during surgery is the susceptibility of the brain to shift as CSF is released and lateral neocortical resection progresses. To overcome this, brain-shift corrections have been performed by using intraoperative MRI after temporal neocortical resection. In 12 patients, nonlinear registration was performed between the preoperative image space, in which tractography was performed, and the intraoperative MRI scan. The subsequent displacement fields were then used to correct the position of the OR. Winston et al. 20 compared the results of this method for brain-shift correction with the results of a cohort of 9 patients who received treatment in an iMRI suite that did not utilize brain-shift correction. They reported that the average shift of the OR was 4.3 mm during the intraoperative scan and 9.3 mm at the end of surgery. The displacement in the anteroposterior axis, which would have significantly affected Meyer’s loop, was limited to a mean displacement of 0.5 mm. Intraoperative scans required 1 hour to complete on average, and iMRI guidance prevented significant VFD that could have precluded driving by all 21 patients, regardless of whether brain-shift correction was applied.

![Intraoperative photographs with OR tractography overlay](image-url)
or not, whereas the non-iMRI historical cohort had a VFD rate of 13% (5/40 patients). Another benefit of utilizing the microscope overlay, instead of a navigated instrument, is that guidance is continuous and does not require the surgeon to look away from the surgical microscope and toward the neuronavigation system. The surgeon can turn the overlay on and off at will.

We report that the OR overlay can also be used to inform fixed retractor placement. In our cohort, patient 4 had significant VFD early in the series. Overlaying preoperative tractography onto the 3-month postoperative MRI scan revealed that neither lateral neocortical resection nor approach to the ventricle transgressed tractography. Instead, a linear hyperdensity that extended 3 cm posteriorly from the resection cavity over the superolateral aspect of the temporal horn was noted at the site of the fixed brain retractor that overlapped with OR tractography (Fig. 5).

After this case, tractography was also used to guide retractor placement and no further VFD occurred.

The main limitation associated with this study is the
lack of a control group that did not undergo OR tractography. This limits the ability to compare rates of VFD and seizure-free outcome. For this reason, we are able to report only the rate of VFD in our cohort without being able to make statistical comparisons. Of note, the most recent published data from our center for the current method for ATLR, in which the basal temporal approach is used to approach the temporal horn through the collateral sulcus and without iMRI, showed a 13% rate of driving-limiting VFD. Preoperative visual field assessment data were available for only 55% of patients in our series because our hospital is a national referral center for epilepsy surgery and some patients were unable to undergo preoperative assessment owing to traveling requirements. Small VFD was noted in 25% (5/20) of patients, but these were preexisting in the 27% (3/11) of patients who underwent preoperative visual field assessment. Therefore, we are unable to ascertain if the VFDs in the remaining 2 patients were due to surgery, but the resection cavities did not overlap with the findings on preoperative tractography. In either event, these small defects did not have functional sequelae and did not affect driving eligibility. In the 1 patient who had significant postoperative VFD, the results of the preoperative visual field assessment were available for comparison and confirmed that this VFD was due to surgery (Fig. 5). Finally, the presented cohort of patients comprised a highly selected group of patients with presumed hippocampal sclerosis who underwent concordant presurgical evaluation or preoperative stereoelectroencephalography. No patients had tumor or gross structural deformity; therefore, it is unclear if our method can be used to treat such patients.

Conclusions

Probabilistic OR tractography can be used during ATLR in a conventional operating theater with a commercial neuronavigation system and microscope. Tractography is useful for guiding the surgical approach to the amygdala and temporal horn of the lateral ventricle, as well as for informing retractor placement. Additional comparative studies are required to determine the incremental benefit of OR tractography on the rate of VFD.

Acknowledgments

This study was funded by grants from the Wellcome Trust (WT106882), Wellcome/EPSRC (203145Z/16/Z), and MRC (G0802012 and MR/M00841X/1).

References

23. Ebeling U, Reulen HJ. Neurosurgical topography of the optic


**Disclosures**

Dr. Ourselin receives non–study-related clinical or research support from Medtronic and Siemens Healthineers.

**Author Contributions**

Conception and design: Vakharia, McEvoy, Ourselin, Duncan.

Acquisition of data: Vakharia, Vos, Winston, Gutman, Wykes, McEvoy, Misericocchi, Sparks. Analysis and interpretation of data: Vakharia, Vos, Sparks. Drafting the article: Vakharia. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Vakharia. Administrative/technical/material support: Vos, Winston, Sparks. Study supervision: McEvoy, Ourselin, Duncan.

**Supplemental Information**

Current Affiliations

Dr. Gutman: Alfred and Austin Hospital, Melbourne, Australia.

**Correspondence**

Vejay N. Vakharia: Queen Square Institute of Neurology, University College London, London, United Kingdom. v.vakharia@ucl.ac.uk.