Is a paradigm shift occurring in functional neurosurgery? Historically, stereotactic surgery was founded on the tenet that a small target, located deep inside the brain, must be validated during the surgery before implementing the final treatment. Even the earliest pioneers, such as Spiegel and Wycis, performed their first procedures with patients awake so that they could be examined and assessed intraoperatively. Soon thereafter, electrophysiology made its way into the operating room with local field potential and single-cell recordings. In fact, functional neurosurgeons evolved as surgical neurologists who depended on the neurological examination and neurophysiology of their patients to confirm successful surgery. These skills for intraoperative target verification required awake patients and were necessary in an era when images of the brain and its deeper structures were not available.

Today, modern imaging with MRI has revealed the regions of the brain that are diseased or involved in treatment for conditions like Parkinson disease. For decades, clinical testing and/or microelectrode recording (MER) of neuronal signatures have been generally recognized as the gold standard for target verification during stereotactic surgery in Parkinson disease and other movement disorders. Now the rapid technological advances in imaging, especially MRI, have created enthusiasm for stereotactic surgery that is image-guided and based on anatomy rather than electrophysiology. In this issue of *Journal of Neurosurgery*, Cui et al. present their experience of performing subthalamic nucleus (STN) deep brain stimulation (DBS) surgery for the treatment of advanced Parkinson disease with a hybrid technique utilizing electrophysiology and intraoperative MRI (iMRI) for electrode placement.

In this study, 110 patients were treated with STN DBS guided with awake, MER, and macroelectrode-stimulation clinical testing. Intraoperative MRI was employed immediately after electrode and lead placement to confirm final electrode positioning before pulse generator implantation. Overall, 56 (27%) of 206 electrodes were repositioned based on the iMRI after microelectrode mapping and clinical testing. The authors were diligent and meticulous in the iMRI assessment of final DBS electrode position; a single revision was performed in 50 cases and two revisions in 6. All electrodes were eventually positioned in the center of the STN as visualized by T2-weighted sequences from a 1.5-T iMRI system. Intraoperative MRI was also helpful in the identification of intracerebral hemorrhage (n = 2), ventricular trajectories (n = 3), and pneumocephalus.

This hybrid use of iMRI and electrophysiology during DBS surgery is innovative. DBS continues to evolve, as most surgeries traditionally rely on either localization based on electrophysiology or, more recently, imaging. A combination assessment, as proposed by Cui et al., represents an iterative advance where electrophysiology-defined surgery is confirmed and correlated intraoperatively with imaging. More information is available to the neurosurgeon, but the manner in which it is prioritized remains unclear. The implementation of iMRI or any other advanced imaging modality during surgery sets a higher standard for stereotactic surgery where the intervention is immediately validated. Soon there will be no tolerance for the discovery of a suboptimal electrode placement on postoperative imaging.

There are two fundamental assumptions of this study which are debatable. First, the authors have valued final electrode localization by iMRI more than positioning with electrophysiology guidance. While there is growing enthusiasm for image-guided DBS surgery in the asleep condition, the most commonly accepted method for DBS placement relies on clinical and/or electrophysiological assessment in the awake state. The rationale for reposition-
ing a DBS electrode after it is apparently positioned with MER and clinical testing remains unproven. Secondly, the authors’ goal of positioning DBS electrodes in the center of the STN has theoretical issues. The traditional concept of the STN organization localizes the motor territory to the dorsolateral region of the nucleus. DBS placement to the center of the nucleus could potentially involve cognitive or mood-related effects with suboptimal alleviation of parkinsonian features.

The primary limitation of the study, however, is the lack of clinical information and outcome data to assess the technique. There is no reporting of Unified Parkinson’s Disease Rating Scale (UPDRS) scores, quality of life measurements, cognitive assessments, or levodopa equivalents to gauge the effectiveness of using iMRI for final electrode placement. With clinical outcome data, the results obtained with this hybrid technique could be compared to results in other series of DBS exclusively utilizing clinical, microelectrode, or image guidance. Until comparative data are available, the question remains whether DBS for PD should be based on anatomical imaging or electrophysiology. Ultimately, a hybrid technique that emphasizes electrophysiology and intraoperative imaging may become the standard for stereotactic surgery and should improve our understanding of deep brain anatomy and its manipulation for treatment.

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Disclosure
The author reports no conflict of interest.

Response
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We thank Professor Elias for his comments on our paper and his thoughts concerning localization of the STN and other clinical information.

Professor Elias agreed with us about the advances in neuroimaging for DBS surgery. Currently, however, the most commonly accepted method for DBS device placement requires conscious clinical and/or electrophysiological assessment. Whether anatomical targeting is superior to MER is unclear. Nevertheless, it is known that anatomical placement of electrodes is associated with successful outcomes. In our study, we emphasized the use of iMRI for surgery, but we do not deny the utility of MER. Both MER and iMRI can be used to pinpoint the STN from distinct electrophysiological and anatomical points of view. MER can record electrical activity from different brain areas, especially in the STN. However, not every patient provides a typical STN signal. Further, even if a typical electrophysiological signal of the STN is obtained, it is difficult to determine whether such a recording is useful for assessing clinical outcomes of DBS treatment. Repeated punctures used to obtain a better electrophysiological signal of the STN also increase the risk of bleeding. Thus, iMRI can provide a timely correction of deviations in MER, reduce MER recording time, avoid multiple blind puncturing, and reduce the risk of bleeding. MER and iMRI are excellent complementary approaches. We have found that the use of iMRI identifies intraoperative hemorrhage, provides a clear indication of the location and amount of hemorrhage, clearly shows the extent of bilateral frontal pneumocephalus, allows assessment of CSF loss (frontal subarachnoid space, lateral ventricles, and third ventricle) and thus the extent of posterior brain shift, and provides the precise location of electrode contacts and lead tract, and can be used as a guide to adjust deviations in coordinates.

We agree with Professor Elias that there are some limitations to our study, for example the lack of UPDRS scores, quality of life measurements, cognitive assessments, or levodopa equivalents to gauge the effectiveness of using iMRI for final electrode placement. However, our emphasis was on the utility of iMRI for DBS implantation, and its description as a technique, rather than assessing outcomes. In a total of 27% of cases, the DBS electrodes were repositioned based on MR imaging, data charts, and graphs, suggesting that iMRI is helpful for localization of anatomical targets and target adjustment of the STN. These iMRI findings suggest that for some patients the target of DBS electrode implantation obtained from preoperative planning and intraoperative procedures is inconsistent with the real target. Currently, we are continuing our studies into the use of iMRI in DBS surgery and are planning to include more clinical information. Of course, future studies will be performed to evaluate the efficacy of using pre- or post-surgery UPDRS scores for long-term follow-up or comparison between groups.