35. Guru KA, Shafiei SB, Khan A, Hussein AA, Sharif M, Esfahani ET. Understanding cognitive performance during robot-assisted surgery. Urology 2015;86:751-7.
36. Guru KA, Esfahani ET, Raza SJ, Bhat R, Wang K, Hammond Y, et al. Cognitive skills assessment during robot-assisted surgery: separating the wheat from the chaff. BJU International 2015;115:166-74.
37. Strangman G, Boas DA, Sutton JP. Non-invasive neuroimaging using near-infrared light. Biological Psychiatry 2002;52: 679-93.
38. Dähne S, Bießmann F, Meinecke FC, Mehnert J, Fazli S, Mtüller KR. Multimodal integration of electrophysiological and hemodynamic signals. 2014 International Winter Workshop on Brain-Computer Interface (BCI). 2014; 1–4.
39. Orihuela-Espina F, Leff DR, James DRC, Darzi AW, Yang GZ. Quality control and assurance in functional near infrared spectroscopy (fNIRS) experimentation. Phys Med Biol 2010;55:3701-24.
40. Tachtsidis I, Leung TS, Chopra A, Koh PH, Reid CB, Elwell CE. False positives in functional near-infrared topography. Adv Exp Med Biol 2009;645:307-14.
41. Bahrami P, Schweizer TA, Tam F, Grantcharov TP, Cusimano MD, Graham SJ. Functional MRI-compatible laparoscopic surgery training simulator. Magn Reson Med 2011;65:873-81.
42. Bahrami P, Graham SJ, Grantcharov TP, Cusimano MD, Rotstein OD, Mansur A, et al. Neuroanatomical correlates of laparoscopic surgery training. Surg Endo 2014;28:2189-98.

A decade of imaging surgeons' brain function (part II): A systematic review of applications for technical and nontechnical skills assessment

Hemel Narendra Modi, MRCS, MEd,[a] Harsimrat Singh, PhD,[a] Guang-Zhong Yang, PhD, FREng,[b] Ara Darzi, MD, FRCS, FACS, FMedSci, HonFREng,[a,b] *and*
Daniel Richard Leff, FRCS, MS (Hons), PhD,[a,b] *London, United Kingdom*

Background. *Functional neuroimaging technologies enable assessment of operator brain function and can deepen our understanding of skills learning, ergonomic optima, and cognitive processes in surgeons. Although there has been a critical mass of data detailing surgeons' brain function, this literature has not been reviewed systematically.*
Methods. *A systematic search of original neuroimaging studies assessing surgeons' brain function and published up until November 2016 was conducted using Medline, Embase, and PsycINFO databases.*
Results. *Twenty-seven studies fulfilled the inclusion criteria, including 3 feasibility studies, 14 studies exploring the neural correlates of technical skill acquisition, and the remainder investigating brain function in the context of intraoperative decision-making* (n = *1), neurofeedback training* (n = *1), robot-assisted technology* (n = *5), and surgical teaching* (n = *3). Early stages of learning open surgical tasks (knot-tying) are characterized by prefrontal cortical activation, which subsequently attenuates with deliberate practice. However, with complex laparoscopic skills (intracorporeal suturing), prefrontal cortical engagement requires substantial training, and attenuation occurs over a longer time course, after years of refinement. Neurofeedback and interventions that improve neural efficiency may enhance technical performance and skills learning.*
Conclusion. *Imaging surgeons' brain function has identified neural signatures of expertise that might help inform objective assessment and selection processes. Interventions that improve neural efficiency may target skill-specific brain regions and augment surgical performance. (Surgery 2017;162:1130-39.)*

From the Department of Surgery and Cancer[a] and Hamlyn Centre for Robotic Surgery,[b] Imperial College London, London, United Kingdom

NEUROIMAGING has the potential to advance our understanding in areas of surgical training and practice for which there remain on-going challenges and controversies, such as expertise development and skills training.[1-14] However, assessment of surgeons' brain function was quiescent until approximately a decade ago, when advances in functional neuroimaging techniques made assessments of operator brain function during surgery both tangible and feasible (see Part I). Our team and other investigators have capitalized on developments that enable subjects to be freely mobile to execute complex maneuvers and allow assessments of brain function in natural and challenging environments. Moreover, there is a critical mass of published research describing the added value of operator brain function in improving surgical training and enhancing patient safety, but to date this literature has not been reviewed in detail. The current review seeks to address this gap in the literature, specifically focusing on the following research questions:

1) Are there differences in neuroimaging signals obtained from novice and expert surgeons during technical and nontechnical skill performance, in which regions of the brain are these differences observed, and how does skills training influence these signals?
2) How do interventions designed to enhance skill acquisition and/or surgical performance modulate brain signals in surgeons?

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology was followed to conduct a systematic database search of Medline, Embase, and PsycINFO up to November 2016. Appropriate keywords and MeSH terms were identified and combined using suitable Boolean operators (Supplementary Material). Additional articles were retrieved from bibliographic searches. The search was limited to studies on humans and English language publications. Studies were included for review based on the following inclusion criteria: (1) published original studies, (2) study participants were surgeons, (3) the dependent variable was brain function measured using established neuroimaging modalities, and (4) the independent variable was any technical or nontechnical skill, or a skill-enhancing intervention. Retrieved articles were independently analyzed by 2 of the authors (H.N.M. and H.S.), and disagreements over inclusion or exclusion were resolved by consensus. A critical synthesis of the extracted data was undertaken to delineate the brain regions crucial for successful performance of specific technical and nontechnical skills in surgery, as well as to assess the impact of specific interventional strategies on brain signals and surgical performance.

RESULTS

Data extraction. As illustrated in Fig 1, 27 articles were eligible for inclusion and comprised feasibility studies (n = 3), investigations of technical skill acquisition (n = 14), intraoperative decision-making (n = 1), neurofeedback (n = 1), robot-assisted technology (n = 5), and surgical teaching (n = 3) (Supplementary Material Table I).

Technical skills and brain function. Functional neuroimaging data successfully acquired during open[15] and laparoscopic[16,17] task paradigms is repeatable,[15] reliable,[15] and resistant to motion artefact.[17] Variations in brain activation associated with technical expertise, and which subserve motor learning, are discussed according to the brain region of interest.

Prefrontal cortex. Changes in activation of the prefrontal cortex (PFC) that accompany expertise development and motor learning in surgery depend upon task complexity (Fig 2). With "simple" tasks, such as open knot tying, novices exhibit greater PFC activation than expert surgeons.[1] However, after a period of training and practice, the prefrontal response of the "trained" novices attenuates as performance improves.[3,4] For more complex skills, such as laparoscopy, prefrontal engagement requires greater practice, and attenuation requires many years of refinement. For example, Ohuchida et al[10] demonstrated that

Supported by the Imperial National Institute for Health Research Biomedical Research Centre and the Imperial Cancer Research UK Centre. The authors have no conflicts of interest to declare.

Accepted for publication May 31, 2017.

Reprint requests: Daniel Richard Leff, FRCS, MS (Hons), PhD, Department of Surgery & Cancer, Imperial College London, St Mary's Hospital Campus, 10th Floor, QEQM Building, Praed Street, London W2 1NY. E-mail: d.leff@imperial.ac.uk.

0039-6060/$ - see front matter

http://dx.doi.org/10.1016/j.surg.2017.09.002